1993 K.7

Hydrogeology and Groundwater Flow of the Drift and Platteville aquifer

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 5
77 WEST JACKSON BOULEVARD
CHICAGO, IL 60604-3590

REPLY TO THE ATTENTION OF:

FEB 09 1994

James R. Stark
Chief, Hydrologic Investigations
Water Resources Division
U.S. Geologic Survey
2280 Woodale Drive
Mounds View, Minnesota 55112

Dear Mr. Stark:

We give the U.S. Geological Survey permission to print "Ground Water Flow of the Drift and Platteville Aquifer System, St. Louis Park, Minnesota" as a Water Resources Investigation Report.

If you have any questions, please call me at (312) 886-7089.

Sincerely,

Darryl Owens
Remedial Project Manager

DO
2/8/94

2/8/94

1/13/94

Doug,

Here's that USGS report for Drift / Platteville. By coincidence, Jim Stark of USGS called me today to see if I could OK it. I told him I was thinking of sending it to you for review. He said Justin Blum had seen it and thought it was OK. If that's the case, I don't know why they didn't finalize it long ago. Anyway if Jim can look at the abstract & let me know what he thinks, that would be good. He probably won't have time to look at the whole thing.

Darryl

Jim MacArthur, Hydrogeologist at MPCA called me on 1/24/94 to say the report is acceptable and does contain any inconsistencies with our previous understanding of the aquifer. He said he had seen drafts of the report before and this <u>final</u> draft is consistent.

Darryl Owens RPM

United States Department of the Interior

TAKE PRIDE IN AMERICA

GEOLOGICAL SURVEY

Water Resources Division
2280 Woodale Drive
Mounds View, MN 55112

612
783-3100

November 15, 1993

Mr. Darryl Owens (HSRM-6J)
U.S. EPA Region V
77 W. Jackson
Chicago, IL 60604

Dear Mr. Owens,

Enclosed is a review copy of "Hydrogeology and Ground-Water Flow of the Drift and Platteville Aquifer System, St. Louis Park, Minnesota" by R. J. Lindgren. The report is the latest of several reports written about the contamination problem in St. Louis Park. Please review the report and return it to us with your comments.

We request your written permission to print the report as a Water-Resources Investigations Report. A letter from you to us with a statement similar to the following sentence would be sufficient:

We give the U. S. Geological Survey permission to print "Hydrogeology and Ground-Water Flow of the Drift and Platteville Aquifer System, St. Louis Park, Minnesota" as a Water-Resources Investigations Report.

The enclosed copy is for review only. It may not be distributed or quoted because it has not been approved by the Director of the U. S. Geological Survey.

Respectfully,

For the District Chief

James R. Stark

James R. Stark
Chief, Hydrologic Investigations

Enclosed

One review copy of "Hydrogeology and Ground-Water Flow of the Drift and Platteville Aquifer System, St. Louis Park, Minnesota."

Copy of past letter from U. S. Environmental Protection Agency

Inter-Agency agreement covering project

#212

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 5
230 SOUTH DEARBORN ST.
CHICAGO, ILLINOIS 60604

REPLY TO THE ATTENTION OF:
5HS-11

MAR 15 1989

Thomas A. Wintershine
District Reports Specialist
U.S. Geological Survey
St. Paul, Minnesota 55101

Dear Mr. Wintershine:

We give the U.S. Geological Survey permission to print "Ground water flow in the St. Peter Aquifer as related to contamination by coal tar derivatives, St. Louis Part, Minnesota" as a Water Resources Investigations Report.

Sincerely,

David Wilson

David Wilson
Remedial Project Manager

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF WASTE PROGRAMS ENFORCEMENT

RECEIVED
JUN 30 1987
Program Support Section

ANDUM

SUBJECT: AUTHORIZATION OF TECHNICAL ASSISTANCE UNDER INTERAGENCY AGREEMENT

FROM: U.S. Environmental Protection Agency
Office of Waste Programs Enforcement (WH-527)
Washington, DC 20460

TO: U.S. Geological Survey
National Center (MS-410)
Reston, VA 22092

Authorization is hereby given by the Office of Waste Programs Enforcement to begin technical assistance in accordance with the scope of work of the Interagency Agreement (IAG) between the U.S. Environmental Protection Agency and the U.S. Geological Survey. The IAG, Work Assignment(WA) number and site identification are as follows:

INTERAGENCY AGREEMENT NO. DW 14932616-01 WA # 001 . EPA Site ID # 5P06

SITE NAME	Reiley Tar		
SITE LOCATION	St. Louis Park, MN		
DESCRIPTION	Hydrogeologic Study		
SCAP LINK	2291	REGION	5
CERCLIS NUMBER (Facility ID)	MND980609804		
TYPE OF ACTION	New Agreement		
ESTIMATED PERIOD OF PERFORMANCE	2/01/87	TO	2/01/89
EPA WA PROJECT MANAGER	Daniel J. Bicknell	PHONE FTS	886-7341
USGS WA PROJECT MANAGER	James R. Stark (St. Paul MN)	PHONE FTS	725-7841

REMARKS: EPA/USGS Total Est. Cost $105,000.00 Partially Funded

APPROVED FUNDING:	PREVIOUS AMOUNT	AMOUNT THIS ACTION	AMENDED TOTAL
	0	$45,000.00	0

Billing and quarterly progress reporting will be in accordance with items 21 and 27 of the IAG. All technical reports described in the EPA Scope of Work and any other deliverables will be sent directly to the EPA WA Project Manager.

Steven L. Klein (202) 475-7081 (FTS) 6/27/87
STEVEN L. KLEIN DATE
EPA PROJECT OFFICER

cc: Steve Ragone, USGS/MS-400
Julie Klaas, EPA/WH-527
EPA Regional Contact
EPA WA Project Manager
IAG File

HYDROGEOLOGY AND GROUND-WATER FLOW OF THE DRIFT AND PLATTEVILLE AQUIFER SYSTEM, ST. LOUIS PARK, MINNESOTA

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report XXXX

PROVISIONAL DRAFT
Subject to Revision
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U. S. Geological Survey

Prepared in cooperation with the
U.S. ENVIRONMENTAL
PROTECTION AGENCY

HYDROGEOLOGY AND GROUND-WATER FLOW OF THE DRIFT AND PLATTEVILLE AQUIFER SYSTEM, ST. LOUIS PARK, MINNESOTA

By R.J. Lindgren

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 93-____

Prepared in cooperation with the
U.S. Enivironmental Protection Agency

Mounds View, Minnesota

1993

U.S. DEPARTMENT OF THE INTERIOR

Bruce Babbitt, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

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For additional information write to:

District Chief
U.S. Geological Survey
2280 Woodale Drive
Mounds View, MN 55112

Copies of this report can be purchased from:

U.S. Geological Survey
Books and Open-File Reports
Box 25425, Mail Stop 517
Federal Center
Denver, CO 80225-0425

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER QUALITY UNITS

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per day (ft/day)	0.3048	meter per day
cubic foot per second (ft^3/s)	0.28317	cubic meter per second
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
inch per year (in/yr)	25.40	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Chemical concentrations are given in metric units. Chemical concentrations of substances in water are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 m/L, the numerical value is equivalent to concentrations in parts per million.

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

HYDROGEOLOGY AND GROUND-WATER FLOW OF THE DRIFT AND PLATTEVILLE AQUIFER SYSTEM, ST. LOUIS PARK, MINNESOTA

By R. J. Lindgren

ABSTRACT

Three aquifers and two confining units have been delineated within the drift underlying the area near the site of a former coal-tar distillation and wood-preserving plant in St. Louis Park, Minnesota. The aquifer system, which consists of the drift aquifers (upper, middle, and lower) and the Platteville aquifer, is called the drift and Platteville aquifer system. The hydrogeologic units of the drift, in descending order, are the upper drift aquifer, the upper drift confining unit, the middle drift aquifer, the lower drift confining unit, and the lower drift aquifer.

The upper drift aquifer has a maximum saturated thickness of about 25 feet. Hydraulic conductivities of the upper drift aquifer range from 1 to 25 feet per day in peat areas and from 50 to 400 feet per day in sand and gravel areas. The upper drift confining unit generally is less than 20-feet thick, with a maximum thickness of about 62 feet. The saturated thickness of the middle drift aquifer generally is 20 to 30 feet in areas where the aquifer is both overlain and underlain by a confining unit. The hydraulic conductivity of the middle drift aquifer ranges from 50 to 500 feet per day. The lower drift confining unit ranges from 0 to about 50 feet in thickness. Model-computed vertical hydraulic conductivities for both the upper and lower drift confining units range from 0.0002 to 0.2 feet per day. The lower drift aquifer consists of discontinuous sand and gravel deposits overlying Platteville Limestone bedrock and has a maximum thickness of about 20 feet.

The drift is underlain by two subcropping bedrock aquifers, the Platteville and the St. Peter. The Platteville aquifer and underlying Glenwood Shale confining unit have been dissected by bedrock valleys in some places and the valleys are filled with drift material.

In the study area water in the drift aquifers and in the Platteville aquifer generally flows from the northwest to the southeast under a hydraulic gradient of about 10 feet per mile. The drift confining units, and the Glenwood Shale confining unit, when present, control the vertical movement of water through the aquifers. Discontinuities in these confining units greatly influence patterns of ground-water flow. Ground-water flow between aquifers is much greater in areas where the confining units is absent, such as in bedrock valleys.

A numerical cross-section ground-water-flow model was used to test hydrologic concepts of flow through the drift aquifers and the Platteville aquifer, particularly the effects of confining units and bedrock valleys on vertical flow. The model has eight layers representing, in descending order: (1) the upper drift aquifer, (2) the upper drift confining unit, (3) the middle drift aquifer, (4) the lower drift confining unit, (5) the lower drift aquifer, (6) the Platteville aquifer, (7) the St. Peter aquifer, and (8) the Prairie du Chien-Jordan aquifer.

Hydraulic heads measured in the drift aquifers and in the Platteville and St. Peter aquifers during December 1987 were used to calibrate the model for steady-state conditions and to specify heads at the model boundaries. The model-calculated hydraulic heads generally were within 0.2 feet of measured hydraulic heads in wells located along the cross-section. A sensitivity analysis indicated that hydraulic heads in the drift aquifers and in the Platteville aquifer were most sensitive to variations in: (1) the horizontal hydraulic conductivities of the middle drift aquifer, (2) the transmissivities of the Platteville and St. Peter aquifers, (3) the vertical hydraulic conductivities of the lower drift confining unit and the drift material filling the bedrock valley, and (4) the vertical hydraulic conductivity of the basal St. Peter confining unit.

A water budget calculated using an 8-layer computer model showed that recharge from infiltration of precipitation to the upper and middle drift aquifers accounts for about 41 percent of the total sources of water. The remaining 59 percent is from subsurface inflow from the west (through specified-head cells). About 70 percent of the outflow from the eastern model boundary was simulated as discharge from the layers representing the Platteville and St. Peter aquifers. The calibrated simulation indicated that about 99 percent of the total leakage of water from the drift aquifers and from the Platteville aquifer to the underlying St. Peter aquifer occurs through areas where the Glenwood Shale confining unit is absent or discontinuous.

Hypothetical changes of the hydraulic properties and the extent of confining units were simulated using the calibrated steady-state model. Increasing the vertical hydraulic conductivity of the lower drift confining unit by a factor of 100 in the western part of the cross-section resulted in: (1) a 0.8 and 0.5 foot mean decline in model-calculated hydraulic heads in the overlying upper drift and middle drift aquifers, respectively, (2) a 0.4 to 0.6 foot mean rise in model-calculated hydraulic heads in the underlying lower drift, Platteville, and St. Peter aquifers, and (3) decreased leakage to the St. Peter aquifer through the bedrock valley in the eastern part of the cross-section model. A hypothetical extension of the Glenwood Shale confining unit along the entire cross-section model resulted in: (1) mean rises in model-calculated hydraulic heads in the drift aquifers and in the Platteville aquifer ranging from 0.7 feet in the upper drift aquifer to 1.3 feet in the lower drift and Platteville aquifers, and (2) a 98 percent reduction in the amount of water leaking from the Platteville aquifer to the underlying St. Peter aquifer.

A contamination plume consisting of coal-tar derivatives exists in the drift aquifers and in the Platteville aquifer underlying the southern part of the plant site and areas to the south and east of the plant site. Model simulations indicate that vertical ground-water flow from the drift aquifers and from the Platteville aquifer to underlying bedrock aquifers is greatest through bedrock valleys. The convergence of flow paths near bedrock valleys and the greater volume of water moving through the valleys would likely result in both elevated concentrations and greater vertical movement of contaminants in these areas.

INTRODUCTION

Ground-water contaminants from a coal-tar distillation and wood-preserving plant (hereinafter referred to as the plant site) that operated from 1918-72 have degraded the quality of water in several aquifers in the vicinity of St. Louis Park, Hennepin County, Minnesota (Hult and Schoenberg, 1984) (fig. 1). Water in aquifers in the drift and in the Platteville Limestone has been contaminated by coal-tar derivatives, a complex mixture of more that 1,000 compounds. The contaminants percolated down to the water table from ponds and wetlands that received run-off and process-water from the plant. The hydrocarbon-fluid phase, which is an undissolved liquid mixture of many individual coal-tar compounds, has moved vertically downward because it is denser than water. Contaminants dissolved in the ground water also have moved laterally within the drift to the southeast and down into the underlying bedrock aquifer (Platteville aquifer). Locally, contaminants have reached another bedrock aquifer (St. Peter aquifer) through bedrock valleys where the overlying confining unit (Glenwood Shale confining unit) has been removed by erosion.

FIGURE 1.--NEAR HERE.

Figure 1.--Location of study area

The U.S. Geological Survey (USGS), in cooperation with the Minnesota Department of Health (MDH), began a study in 1978 to develop a detailed understanding of the transport of coal-tar derivatives through the ground-water system in the St. Louis Park area (Hult and Schoenberg, 1984). The USGS, in cooperation with the Minnesota Pollution Control Agency (MPCA), began a study in 1983 to construct, calibrate, test, and apply a numerical model that simulates ground-water flow in the St. Peter and Prairie du Chien-Jordan aquifers in the St. Louis Park area to study the movement of coal-tar derivatives in these aquifers (Stark and Hult, 1985). The USGS, in cooperation with the U.S. Environmental Protection Agency, began a study in 1987 to: (1) evaluate the direction and rate of movement of ground water in the St. Peter aquifer under past and current (1987) pumping conditions and under proposed gradient-control conditions and (2) develop a better understanding of hydrogeology and ground-water flow in the drift aquifers and in the Platteville aquifer. Lorenz and Stark (1990) addressed the first objective by describing ground-water flow in the St. Peter aquifer and the effects of proposed pumping scenarios. The second objective will be addressed in this report.

Previous studies completed by the U.S. Geological Survey have dealt primarily with understanding ground-water flow and contaminant transport in the St. Peter and Prairie du Chien-Jordan aquifers and in evaluating possible options for remedial actions in those aquifers. Recent activities by local, State, and Federal regulators include the evaluation of monitoring and remedial actions in the drift aquifers and in the Platteville aquifer. The aquifer system, which consists of the drift aquifers (upper, middle, and lower), the confining units (upper and lower), and the Platteville aquifer, is hereinafter referred to as the drift and Platteville aquifer system. Because the stratigraphy and ground-water flow in the drift and Platteville aquifer system are complex, a better understanding of ground-water flow is essential to evaluate plans for additional monitoring and for implementation of gradient-control measures in the aquifers.

Purpose and Scope

This report describes the hydrogeology and ground-water flow in the drift and Platteville aquifer system near the plant site in St. Louis Park, Hennepin County, Minnesota (fig. 1). Hydrogeologic units underlying the drift aquifers and the Platteville aquifer are discussed only to the extent necessary to describe ground-water flow in the drift and Platteville aquifer system. A numerical ground-water-flow model was constructed and calibrated for steady-state conditions to represent a cross-section through the study area. The model was used to test hydrologic concepts of flow through the drift and Platteville aquifer system and to investigate the effects of changes in hydraulic properties and fluxes on hydraulic heads and ground-water flow.

Previous Investigations

Numerous studies have been made of the drift and Platteville aquifer system hydrogeology and the contamination problems in St. Louis Park. In 1933, McCarthy Well Company concluded that contamination was coming from the plant site through "several old wells being used to drain creosote away into the ground" (Stark and Hult, 1985, pg. 6). The MDH (1938) identified nine wells in the area containing water with either a phenolic or tar-like taste. In 1946, the concentration of phenolic compounds in water from St. Louis Park well 4, located southeast of the plant site and completed in the Prairie du Chien-Jordan aquifer, was 0.1 mg/L (Hickok, 1969). Hickok (1969) reported that measurements made in 1969 indicated possible contamination of other wells and suggested additional studies be made to better evaluate the contamination problem.

A study by Sunde (1974) concluded that contamination of the St. Peter and Prairie du Chien-Jordan bedrock aquifers resulted from flow of contaminated water through wells connecting more than one aquifer. The MDH (1974) reported on the quality of water from private and municipal wells in the St. Louis Park area. A compilation of geological information on the St. Louis Park area was completed by Olson and others (1974). National Biocentric (1976a; 1976b) analyzed drift deposits underlying the northern part of the plant site for organic contaminants.

Barr Engineering Co. (1976 and 1977) installed 3 piezometers and 14 drift and 2 bedrock monitoring wells. Cores from 14 borings were analyzed for phenolic and benzene-extractable compounds. Based on analyses of these cores Barr Engineering Co. estimated that removal of the drift, which was contaminated with more than 1,000 milligrams per kilogram of benzene-extractable constituents, would require excavation of 400,000 cubic yards of soil (1976). Water samples in the drift were analyzed for phenolic compounds, oil and grease, and selected inorganic constituents. Water in the drift was found to be contaminated at least 1,000 feet from the plant site. Specific remedial actions were recommended by Barr Engineering Co. to control ground-water contamination in the drift. Barr Engineering Co. (1977) concluded that the source of the low, but detectable, levels of phenolic compounds in the municipal wells completed in the Prairie du Chien-Jordan aquifer could not be determined from the available data. The MDH (1977 and 1978) measured the concentrations of polynuclear aromatic hydrocarbons (PAH) in municipal water supplies, assessed the health-risk implications, and outlined additional data needs.

Hult and Schoenberg (1984) conducted a preliminary evaluation of ground-water contamination by coal-tar derivatives in the St. Louis Park area. At least 25 ungrouted or partly cased wells in the area were considered by Hult and Schoenberg to possibly permit contaminated water from near-surface aquifers to flow into deeper bedrock aquifers along or through the well bores (1984). Flow rates of 20 to 150 gal/min from the Platteville and St. Peter aquifers to the Prairie du Chien-Jordan aquifer were measured in five wells. The water was contaminated in four of the five wells. Dissolved coal-tar constituents in the drift and the Platteville aquifer system had moved at least 4,000 feet downgradient to a drift-filled bedrock valley. Contaminated water with a concentration of approximately 2 mg/L dissolved organic carbon was entering the underlying St. Peter aquifer. Chemical analyses of water pumped from observation wells indicated soluble, low-molecular-weight compounds were moving preferentially through the drift and Platteville aquifer system.

Stark and Hult (1985) developed a numerical three-dimensional ground-water-flow model of the Prairie du Chien-Jordan aquifer and overlying hydrogeologic units, including glacial deposits in bedrock valleys, the St. Peter Sandstone aquifer, and the basal confining unit of the St. Peter Sandstone, in the St. Louis Park area. The model was used to evaluate the movement of coal-tar derivatives from the plant site. The model was also used to investigate the effects of cones of impression (locally persistent mounds in the potentiometric surface near wells) created by water introduced into the Prairie du Chien-Jordan aquifer through wells open to more than one aquifer. The simulations indicated that cones of impression could have a significant effect on the transport of contaminants in the Prairie du Chien-Jordan aquifer. The simulations also were used to investigate the response of hydraulic heads in the Prairie du Chien-Jordan aquifer to pumping from wells located upgradient from the plant site. Stark and Hult concluded that local hydraulic gradients would be altered to the extent that contaminants would move from the area of the plant site to these wells (1985). Simulations of a gradient-control plan using 5 discharge wells indicated that the actions would be effective in limiting the extent of the contaminated plume in the Prairie du Chien-Jordan aquifer. The model-calculated hydraulic heads, however, were sensitive to changes in withdrawal rates at wells not intended to be under the control of the plan. Management of discharge from these wells also would be important to the overall effectiveness of the remedial-action plan.

Lorenz and Stark (1990) used a numerical model of ground-water flow to: (1) simulate ground-water flow in the Prairie du Chien-Jordan and St. Peter aquifers in St. Louis Park, Minnesota, (2) test hypotheses about the movement of ground water contaminated with coal-tar derivatives, and (3) simulate alternatives for reducing the downgradient movement of contamination in the St. Peter aquifer. The model also was used to simulate the effects of multiaquifer wells open to both the St. Peter and Prairie du Chien-Jordan aquifers. The simulations indicated that sustained pumping from these multiaquifer wells would cause cones of depression in both aquifers and could limit the downgradient migration of contaminants in the St. Peter aquifer and in the Prairie du Chien-Jordan aquifer. Model simulations also indicated that areal differences in vertical leakage to the St. Peter aquifer, which may exist in bedrock valleys, are not likely to significantly affect the general patterns of ground-water flow.

Acknowledgments

Appreciation is expressed to the staff of the MPCA, in particular to Justin Blum, for guidance and assistance with data compilation and water-level measurements and for valuable discussions of site history.

HYDROGEOLOGY OF STUDY AREA

During the Pleistocene Epoch four continental glaciers covered the bedrock surface in east-central Minnesota with drift. The thickness of the drift in the study area ranges from about 70 feet, under the plant site, to about 125 feet, in bedrock valleys. The vertical and horizontal distribution of aquifers and confining units within the drift is highly variable and complex. Hydrogeologic units in the drift defined for this study are shown in table 1.

TABLE 1.--NEAR HERE.

Table 1.--Geologic and water-bearing characteristics of hydrogeologic units
[Modified from Stark and Hult (1985)]

Geologic unit	Approximate range in thickness (feet)	Geologic characteristics	Water-bearing characteristics	Hydrogeologic units defined for this study
		All drift units		
Glacial drift	70-125	Undifferentiated over most of the St. Louis Park area. Till, outwash and valley train sand and gravel, lake deposits and alluvium; vertical and horizontal distribution of units is complex.	Distribution of aquifers and confining beds within the drift is poorly known outside the area of the plant site. Stratified, well-sorted deposits of sand and gravel yield moderate to large supplies of water to wells (240-2,000 gallons per minute).	
		Individual drift units		
Upper drift peat, sand, and gravel	0-25	Includes peat underlying lowland areas and sand and gravel underlying upland areas. Generally absent northwest and southeast of plant site.	Horizontal hydraulic conductivity of peat ranges from less than 1 to about 25 feet per day at depths greater than 1-foot below land surface and decreases with increasing depth. Horizontal hydraulic conductivity of aquifer in sand and gravel areas ranges from 50 to 400 feet per day based on grain size.	Upper drift aquifer
Upper drift clay and till	0-62	Includes lake sediments, clay, till, and sandy till. Generally present in a band about 0.5 to 1.5 miles wide trending from northwest to southeast near the plant site.	Vertical hydraulic conductivity ranges from 0.00004 to 0.2 feet per day.	Upper drift confining unit
Middle drift sand and gravel	5-80	Medium-to-coarse sand and fine gravel, silty sand.	Horizontal hydraulic conductivity ranges from 50 to 500 feet per day based on grain size. Transmissivity near plant site is about 10,000 feet squared per day.	Middle drift aquifer
Lower drift clay and till	0-50	Includes clay, till, and sandy till.	Vertical hydraulic conductivity ranges from 0.00004 to 0.2 feet per day.	Lower drift confining unit

Table 1.--Geologic and water-bearing characteristics of hydrogeologic units--Continued

Geologic unit	Approximate range in thickness (feet)	Geologic characteristics	Water-bearing characteristics	Hydrogeologic units defined for this study
Lower drift sand and gravel	0-20	Medium-to-coarse sand and fine gravel, weathered limestone and gravel rubble. Generally present in a northwest-to-southeast trending band about 0.3 to 1.0 mile wide transecting the plant site, and generally absent outside this band.	Horizontal hydraulic conductivity ranges from 100 to 500 feet per day based on grain size.	Lower drift aquifer
		Bedrock units		
Decorah Shale	0-95	Shale, bluish-green to bluish-gray, blocky. Locally present in southern part of Hennepin County.	Confining bed.Vertical hydraulic conductivity estimated to be as low as 0.000001 feet per day.	
Platteville Limestone	0-30	Dolomitic limestone and dolomite, gray to buff, thin to medium bedded, some shale partings contain sand and gravel of glacial origin. Solution channels and fractures are concentrated in upper part. Dissected by erosion.	Hydraulic conductivity primarily from fractures, Platteville open joints, and solution channels. Specific aquifer capacities of wells generally are between 10 and 100 gallons per minute per foot of drawdown, if pumped at about 12 gallons per minute for 1 hour. Results from one aquifer test indicate the transmissivity of the unit is about 9,000 feet squared per day.	Platteville aquifer
Glenwood Shale	0-15	Shale and claystone, green to buff, plastic to slightly fissile, lower 3 to 5 feet grade from claystone with disseminated sand grains to sandstone with clay matrix. Dissected by erosion.	Very low hydraulic conductivity. Vertical hydraulic conductivity is estimated to be about 0.00001 feet per day based on laboratory measurements of core samples.	Glenwood Shale confining unit
St. Peter Sandstone	0-200	Sandstone, white to yellow, very well sorted, very fine- to medium-grained, poorly cemented, quartzose. Lower 5 to 65 feet consist of siltstone and shale. Generally present in most of the southern two-thirds of Hennepin County. Locally absent due to erosion.	Reported vertical hydraulic conductivity of basal confining unit as low as 0.000001 feet per day.	St. Peter aquifer Basal St. Peter confining unit

Table 1.--Geologic and water-bearing characteristics of hydrogeologic units--Continued

Geologic unit	Approximate range in thickness (feet)	Geologic characteristics	Water-bearing characteristics	Hydrogeologic units defined for this study
Prairie du Chien Group	0-170	Dolomite, sandstone, sandy dolomite, light Chien Group brown, buff, gray; thinly to thickly bedded. Locally absent due to erosion.	Hydraulic conductivity is due to fractures, open joints, and solution channels. Generally yields more than 1,000 gallons per minute to high-capacity wells.	Prairie du Chien-Jordan aquifer
Jordan Sandstone	0-130	Sandstone, white to pink, fine- to coarse-grained, moderately well cemented, quartzose to dolomic. Locally absent due to erosion.	Hydraulic conductivity is mostly intergranular but may be due to open joints in cemented zones. Generally yields more than 1,000 gallons per minute to high-capacity wells. Supplies about 80 percent of ground water pumped in the Twin Cities Metropolitan Area.	
St. Lawrence and Franconia Formations	150-250	Siltstone and sandstone, gray to green, poorly sorted, glauconitic, and dolomitic.	Confining bed. Vertical hydraulic conductivity ranges from 0.2 to 0.001 feet per day.	St. Lawrence-Franconia confining unit

The study area is underlain by a thick sequence of sedimentary rocks (as much as 1,000 ft), ranging in geologic age from the Precambrian Period to the Ordovician Period. The sedimentary rocks were deposited in a north-south trending trough in the Precambrian rock surface. The deepest part of the trough, commonly referred to as the Twin Cities Artesian Basin, lies directly beneath the Twin Cities Metropolitan Area. The sedimentary rocks in the basin, with the exception of the Hinckley Sandstone (Precambrian Period), were deposited in Cambrian and Ordovician seas. The rock record is absent from the Middle Ordovician Period to the Quaternary Period. The bedrock surface in the study area is dissected by valleys that were formed either from the Middle Ordovician Period to the Quaternary Period or during the interglacial periods (Norvitch and others, 1974) (fig. 2). Descriptions of the bedrock and hydrogeologic units discussed in this report and their positions in the geologic column are shown in table 1.

FIGURE 2.--NEAR HERE.

Figure 2.--Map showing trace of hydrogeologic sections and location of plant site, bedrock valleys, and peat areas

Hydrogeologic Units

The detailed stratigraphy of the drift is complex. Barr Engineering Co. (1976, 1977) and Hult and Schoenberg (1984) identified three areally persistent units of hydrogeologic significance: (1) the middle drift aquifer of glacial sand and gravel; (2) the upper drift confining unit, an overlying confining bed of lake deposits and till; and (3) an underlying basal drift complex of till, outwash, valley-fill deposits, and deeply weathered bedrock. Hult and Schoenberg (1984) described a fourth unit, the upper drift aquifer, as being poorly defined and discontinuous in the study area.

Three aquifers and two confining units were delineated in this study. The vertical distribution of aquifers and confining units is illustrated for two hydrogeologic sections (fig. 3). The drift aquifers defined in the study area are the upper drift, middle drift, and lower drift aquifers. The term combined drift aquifer refers to the areas where drift confining units are absent (fig. 3). The drift confining units defined in the study area are the upper drift confining unit and the lower drift confining unit. The upper drift aquifer, middle drift aquifer, and upper drift confining unit discussed in this report correspond to hydrogeologic units identified by Barr Engineering Co. (1976, 1977) and Hult and Schoenberg (1984). The lower drift confining unit and lower drift aquifer defined in this report comprise the basal drift complex identified in those two reports.

FIGURE 3.--NEAR HERE.

Figure 3.--Hydrogeologic sections showing hydrogeologic units

The upper drift aquifer ranges in composition from peat, underlying the plant site and the area to the south near Minnehaha Creek, to sand and gravel, underlying most of the study area (fig. 4). The aquifer generally is absent northwest of the plant site and in the southeast part of the study area where till is present at the land surface. The aquifer is under water-table (unconfined) conditions throughout the study area. At some locations the surficial sand and gravel is unsaturated (fig. 4). The saturated thickness of the upper drift aquifer ranges from zero to 25 ft (fig. 4). Based on the grain-size distribution, the hydraulic conductivity of the aquifer in areas of sand and gravel ranges from about 50 to 400 ft/d. Hydraulic conductivity values for peat decrease with increasing depth below the land surface. Reported values range from less than 1 to about 25 ft/d at depths greater than about 1 ft. Furthermore, the vertical hydraulic conductivity of peat generally is considered to be much less (by orders of magnitude) than the horizontal hydraulic conductivity (Tom Gullett, Minnesota Department of Natural Resources, written commun., 1990).

FIGURE 4.--NEAR HERE.

Figure 4.--Map showing saturated thickness of upper drift aquifer

The upper drift aquifer is underlain by the upper drift confining unit, a discontinuous confining bed composed of lake deposits, silty to sandy clay, and till. The upper drift aquifer is continuous with the underlying middle drift aquifer where the upper drift confining unit is absent. The upper drift confining unit generally is present in a band about 0.5- to 1.5-miles wide trending from the northwest to the southeast in the study area and underlies all but the southeast corner of the plant site (fig. 5). The thickness of the confining unit generally is less than 20 ft, but is as much as 62 ft where it is present at the land surface. Norvitch and others (1974) give values of vertical hydraulic conductivity for clays and till with varying amounts of sand ranging from 0.00004 to 0.2 ft/d. Hult and Schoenberg (1984) report that till has a vertical hydraulic conductivity as low as 0.0009 ft/d near the plant site.

FIGURE 5.--NEAR HERE.

Figure 5.--Map showing thickness of upper drift confining unit

The saturated thickness of the middle drift aquifer ranges from about 5 ft to about 80 ft (fig. 6). Sand and gravel extends from land surface to the base of the middle drift aquifer where the upper drift confining unit is absent (figs. 4 and 5). The greatest saturated thicknesses are south and east of the plant site where the middle drift aquifer is under unconfined conditions. The aquifer is under confined conditions in a northwest-to-southeast trending band where the upper drift confining unit is present. The aquifer is under unconfined conditions to the south and east where the overlying upper drift confining unit is absent. The saturated thickness generally is about 20 to 30 ft in areas where the aquifer is both overlain and underlain by a confining unit. The composition of the aquifer varies from silty sand to medium-to-coarse grained sand and fine gravel. Hult and Schoenberg (1984) report the middle drift aquifer has a transmissivity as high as about 10,000 ft^2/d. Based on the grain-size distribution, the hydraulic conductivity of the aquifer ranges from about 50 to 500 ft/d.

FIGURE 6.--NEAR HERE.

Figure 6.--Map showing saturated thickness of middle drift aquifer

The middle drift aquifer is underlain by the basal drift complex, which consists of till, outwash, valley-fill deposits, and deeply weathered bedrock.The basal drift complex can be partitioned into: (1) an upper unit that is predominantly sandy to silty clay and till, hereinafter referred to as the lower drift confining unit; and (2) a lower unit that consists of discontinuous sand and gravel deposits overlying the Platteville Limestone bedrock, hereinafter referred to as the lower drift aquifer. The thickness of the lower drift confining unit ranges from 0 to 50 ft where the underlying lower drift aquifer is present (fig. 7). The lower drift confining unit generally is about 5- to 20-ft thick in the central part of the study area near the plant site. At some locations (underlying the plant site on section A-A', fig. 3) sand and gravel extends from the base of the upper drift confining unit to the bedrock surface. At places where both the upper and lower drift confining units are absent, sand and gravel extends from the land surface to the bedrock surface. Continuous sequences of sand and gravel extending from land surface, or from the base of the upper drift confining unit to the bedrock, do not cover continuous areas of mappable size.

FIGURE 7.--NEAR HERE.

Figure 7.--Map showing thickness of lower drift confining unit

The saturated thickness of the lower drift aquifer ranges from 0 to about 20 ft, where it is overlain by the lower drift confining unit. (fig. 8). The lower drift aquifer generally is present in a northwest-to-southeast trending band (about 0.3 to 1.0 mile wide) transecting the plant site and generally absent outside this band (fig. 8). The lower drift aquifer generally is under confined conditions, except at those sites where both the upper and lower drift confining units are absent. The combination of the middle and lower drift aquifers is as much as 69-ft thick at sites where the lower drift confining unit is absent and the middle and lower drift aquifers are continuous (fig. 8). The lower drift aquifer is composed of medium-to-coarse grained sand and fine gravel. Locally, the gravel includes weathered limestone rubble and coarse gravel. The hydraulic conductivity of the lower drift aquifer ranges from about 100 to 500 ft/d, based on the grain-size distribution.

FIGURE 8.--NEAR HERE.

Figure 8.--Map showing thickness of lower drift aquifer

Previous studies conducted in the Twin Cities Metropolitan Area have combined the Decorah Shale, Platteville Limestone, and Glenwood Shale into a single regional confining unit (Guswa, Siegel, and Gillies, 1982; Stark and Hult, 1985; Schoenberg, 1990; Lindgren, 1990). Locally, however, the Platteville Limestone yields small to moderate supplies of water to wells; therefore, it is classified as an aquifer for the purposes of this study. The Platteville aquifer underlies the drift over most of the study area. The Platteville aquifer and underlying Glenwood Shale confining unit are dissected by bedrock valleys in the central and southeastern parts of the study area (fig. 2), where the drift is underlain by the St. Peter aquifer (Olsen and Bloomgren, 1989). Olson and others (1974) suggested the bedrock valleys in the St. Louis Park area were formed during glacial periods by streams that formed in front of the glacial margin (proglacial streams). Valleys possibly eroded by preglacial or proglacial streams also may have been substantially modified by plucking and abrasion beneath the glaciers (Hult and Schoenberg, 1984).

The Platteville aquifer is a gray to buff, thin-to-medium bedded dolomitic limestone and dolomite with some shale partings, and ranges from 0- to about 30-ft thick in the study area (fig. 9). The aquifer is under confined conditions, except in areas where both the upper drift and lower drift confining units are absent (section A-A', fig. 3). Ground-water flow in the Platteville aquifer primarily is through fractures, open joints, and solution channels. Fractures and solution channels are concentrated in the upper part of the aquifer.Specific capacities of wells completed in the aquifer generally are between 10 and 100 gallons per minute per foot of drawdown (Stark and Hult, 1985).Results from one aquifer test indicate the transmissivity of the aquifer is about 9,000 ft^2/d (Stark and Hult, 1985). Rocks with secondary solution cavity and fracture permeability, such as the Platteville aquifer, often have heterogeneous hydraulic properties that differ widely within the aquifer.Liesch (1973) has documented large local differences in the transmissivity and storage coefficient of the Platteville aquifer near Minnehaha Creek in Minneapolis. Hult and Schoenberg (1984), however, state that short-term pumping tests indicate the hydraulic characteristics of the Platteville aquifer, particularly transmissivity, are reasonably uniform in the St. Louis Park area.

FIGURE 9.--NEAR HERE.

Figure 9.--Map showing thickness of Platteville aquifer

The Platteville aquifer is underlain by the Glenwood Shale confiningunit, a green to buff, plastic to slightly fissile shale and claystone. The Glenwood Shale confining unit was dissected by erosion and is discontinuous in the study area, ranging from 0 to about 15 ft in thickness. Because commonly it is not recorded in water-well logs, detailed information about the unit's thickness and the location of possible discontinuities is lacking, particularly near the bedrock valleys. The confining unit, where present, impedes the flow of ground water between the Platteville aquifer and the underlying St. Peter aquifer. The vertical hydraulic conductivity of the confining unit is estimated to be about 10^{-10}ft/s (9 x 10^{-6}ft/d), based on laboratory measurements of core samples (Hult and Schoenberg, 1984).

The St. Peter aquifer is a white to yellow, fine-to medium-grained, well-sorted, friable sandstone. Near the plant site the St. Peter aquifer is about 125-ft thick. The aquifer is under confined conditions. Norvitch and others (1974) report hydraulic conductivities for the St. Peter aquifer ranging from about 1 to 25 ft/d. Stark and Hult (1985) report a hydraulic conductivity of 20 ft/d for the St. Peter aquifer in the St. Louis Park area.

The base of the St. Peter Sandstone generally consists of 5 to 65 ft of siltstone and shale. This low-permeability bed is referred to as the basal St. Peter confining unit. It acts as a confining unit within the ground-water-flow system. The basal St. Peter confining unit impedes the flow of ground water between the St. Peter aquifer and the underlying Prairie du Chien-Jordan aquifer. Stark and Hult (1985) report a vertical hydraulic conductivity of 0.0009 ft/d for the basal St. Peter confining unit in the St. Louis Park area. Norvitch and others (1974) report vertical hydraulic conductivities as low as 10^{-6} ft/d for the basal St. Peter confining unit in the Twin Cities Metropolitan Area.

GROUND-WATER FLOW

Water in the drift aquifers and in the Platteville aquifer generally flows from west to east across the study area under a hydraulic gradient of about 10 ft/mi (figs. 10 and 11). Southeast of the plant site water in the drift and Platteville aquifer system generally flows from the northwest to the southeast. Water in the underlying St. Peter and Prairie du Chien-Jordan aquifers also generally flows from west to east across the study area, with a northwest to southeast component of flow southeast of the plant site. The potentiometric surface of the upper and the middle drift aquifers (fig. 10) represents a composite of the hydraulic heads in both aquifers. Hydraulic heads in the two aquifers are similar at any given location in the study area generally (within about 0.1 ft). Combining the available data gives a more complete representation of the potentiometric surface because available data in each aquifer unit is limited. The directions of ground-water flow and hydraulic gradients of the upper drift aquifer, the middle drift aquifer, and the Platteville aquifer are similar (Hult and Schoenberg, 1984). Available water-level measurements indicate that hydraulic heads in the lower drift aquifer are similar (within 0.1 ft) to those in the Platteville aquifer at the same location.

FIGURE 10.--NEAR HERE.

FIGURE 11.--NEAR HERE.

Figure 10.--Map showing composite potentiometric surface of the upper and middle drift aquifers, December 1987

Figure 11.--Map showing potentiometric surface of the Platteville aquifer, December 1987

Sources of water to the drift and Platteville aquifer system in the study area are infiltration from precipitation and ground-water inflow to the drift and Platteville aquifers from the west. Norvitch and others (1974) estimated that the mean recharge to the water table, calculated as precipitation minus evapotranspiration, is 6.4 in/yr in the Twin Cities Metropolitan Area. Helgeson and Lindholm (1977) estimated recharge to the unconfined drift aquifer underlying the Anoka Sand Plain in the northern part of the Twin Cities Metropolitan Area to be 11.1 in/yr, based on hydrograph analysis. The amount of ground-water inflow to the drift and Platteville aquifer system in the study area is not known because of a lack of data beyond the immediate area of the plant site.

Sources of discharge from the drift and Platteville aquifer system in the study area are (1) ground-water outflow from the drift and Platteville aquifers to the east, (2) ground-water discharge to surface-water bodies, (3) ground-water evapotranspiration, (4) ground-water withdrawals by wells, and (5) downward leakage to the underlying St. Peter aquifer. The amount of ground-water outflow from the drift and Platteville aquifer system through the eastern study-area boundary is not known because of a lack of data beyond the immediate area of the plant site.

Ground water from the upper drift aquifer discharges to Minnehaha Creek, and ground water from both the upper drift and deeper aquifers discharges to the lakes near the eastern boundary of the study area. Low-flow discharge measurements in November 1978, at four locations on Minnehaha Creek, indicated discharges of 10.9, 11.7, 14.1, and 12.8 ft^3/s (Hult and Schoenberg, 1984). The observed differences in streamflow between measuring points represent net gains or losses of the stream from or to the ground-water system. A portion of each observed difference (as much as 5 percent of measured streamflows) may be due to measurement errors. The amount of ground-water discharge to the lakes is not known.

Discharge from the drift and Platteville aquifer system by ground-water evapotranspiration occurs by direct evaporation of water from the water table where the water table is at or near the land surface, and transpiration by plants where the water table is within the rooting depth of plants (usually less than about 10 ft). The amount of ground-water evapotranspiration in the study area is not known, but may be significant in the bog areas where the water table is near the land surface.

Discharge of ground water by withdrawals from wells in the study area is considered negligible. Prior to 1988, no large-capacity wells withdrew water from the drift and Platteville aquifer system. Beginning in 1988, remedial measures were begun to capture and control the spread of contaminated ground water in the drift and Platteville aquifer system, with gradient-control wells withdrawing ground water from the drift and Platteville aquifers. Otherwise, no high-capacity wells are known to obtain water supplies from the drift and Platteville aquifer system in the study area. The amount of water lost from the drift and Platteville aquifer system by the downward leakage of water to the underlying St. Peter aquifer is not known.

Horizontal and vertical directions of flow in the drift and Platteville aquifer system may be illustrated using hydrogeologic sections and equipotential lines (fig. 12). The directions of ground-water flow in the drift and Platteville aquifer system are perpendicular to the equipotential lines, as shown in fig. 12. Ground-water flow is predominantly horizontal in aquifers, as indicated by small variations in hydraluic head vertically within aquifer units. Vertical differences in hydraulic head within the middle drift aquifer generally are less than 0.03 ft and flow within the aquifer is primarily horizontal. Ground-water flow in confining units has a substantial vertical component. The difference in hydraulic heads between the top and bottom of the basal drift complex, comprised of the lower drift confining unit and the lower drift aquifer, ranges from about 0.15 ft to about 0.60 ft, with heads decreasing with increasing depth. The relatively large vertical gradients indicate the vertical leakage of water out of the middle drift aquifer downward through the basal drift complex. Hydraulic head differences within the Platteville aquifer are not well known because of limited data, but Hult and Schoenberg (1984) indicate that significant vertical gradients may exist within the aquifer.

FIGURE 12.--NEAR HERE.

Figure 12.--Hydrogeologic section showing hydraulic heads in December 1987, equipotential lines, and direction of ground-water flow

The confining units control the vertical movement of water through the drift and Platteville aquifer system. Water leaks downward (1) from the upper drift aquifer to the middle drift aquifer through the upper drift confining unit, (2) from the middle drift aquifer to the lower drift aquifer or the Platteville aquifer through the lower drift confining unit, and (3) from the Platteville aquifer to the St. Peter aquifer through the Glenwood Shale confining unit. The amount of leakage depends on the vertical hydraulic conductivity and thickness of the confining unit, and the difference in hydraulic heads between the aquifers. Discontinuities in the confining units affect vertical flow in the drift and Platteville aquifer system. The absence of low-permeability material separating aquifer units allows for relatively unimpeded downward leakage of water. Therefore, discontinuities in confining units may serve as preferential pathways for ground-water flow.

Winter and Pfannkuch (1976) discussed the hydrogeologic significance of drift-filled bedrock valleys in the Twin Cities Metropolitan Area. They suggested that many of these bedrock valleys may be filled with coarse-grained deposits and could provide preferential pathways for ground-water flow and for the movement of contaminants. The Platteville aquifer and Glenwood Shale confining unit have been removed by erosion, leaving bedrock valleys in the central and southeastern parts of the study area; the valleys are filled with drift. The vertical hydraulic head difference between the middle drift aquifer and the Platteville aquifer ranges from less than 0.1 ft at observation wells farthest from the bedrock valleys to as much as about 10 ft near the bedrock valleys. These vertical hydraulic head differences indicate that the vertical leakage of water out of the middle drift aquifer through the lower drift confining unit is greater in the vicinity of the bedrock valleys than away from them. Also, the hydraulic head difference between the Platteville and St. Peter aquifers ranges from about 20 ft in areas where the Platteville aquifer is underlain by the Glenwood Shale confining unit to nearly zero near the bedrock valleys. The similarity in hydraulic heads and lack of a significant vertical gradient (between the Platteville and St. Peter aquifers) may indicate lateral movement of water out of the Platteville aquifer and into the drift filling the bedrock valleys.

Cross-section Model

A numerical cross-section ground-water-flow model was constructed and calibrated for steady-state conditions. The cross-section model was used to test hydrologic concepts of flow through the drift and Platteville aquifer system, particularly the effects of confining units and bedrock valleys on vertical flow. The numerical model used for this study was the U.S. Geological Survey modular three-dimensional finite-difference ground-water-flow model developed by McDonald and Harbaugh (1988). The model uses finite-difference methods to obtain approximate solutions to partial-differential equations of ground-water flow. The model incorporates horizontal and vertical flow equations, aquifer hydraulic properties, and recharge to and discharge from the aquifers to calculate hydraulic heads in the aquifers.

The use of particle-tracking techniques to generate path lines and time-of-travel information from the results of numerical models can be helpful in analyzing ground-water-flow systems. A particle-tracking post-processing package developed by Pollock (1989) was used to compute ground-water-flow path lines based on output from steady-state simulations obtained with the U.S. Geological Survey modular model. The particle-tracking package graphically presents the results of the path-line calculations. Path lines are calculated using a semi-analytical particle-tracking scheme. Given the initial position of a particle anywhere in a model cell, the coordinates of any other point along the path line within the cell, and the time of travel between them, can be computed directly.

A conceptual model was formulated based on the hydrogeologic setting, aquifer characteristics, aquifer recharge and discharge, and aquifer and confining unit boundary conditions. The conceptual model is a qualitative description of the known hydraulic characteristics and functioning of the hydrogeologic system. Simplifying assumptions are necessary to mathematically represent the hydrogeologic system. The major concepts of flow, the associated assumptions, and the boundary conditions necessary for the model are

1. The upper drift aquifer, the upper drift confining unit, and the middle drift aquifer are recharged by infiltration of precipitation where they are not overlain by other hydrogeologic units.

2. The upper drift aquifer is under unconfined conditions. The middle drift aquifer is under both unconfined and confined conditions. The lower drift, Platteville, St. Peter, and Prairie du Chien-Jordan aquifers are under confined conditions.

3. Some natural hydrologic boundaries lie beyond the modeled cross-section transect, and ground water flows laterally across arbitrarily imposed model boundaries.

4. The trace of the cross-section is aligned with the major horizontal flow paths in the aquifers and no significant horizontal flow, not aligned with the trace, occurs in the drift and Platteville aquifer system.

5. The volume of water that moves vertically through the base of the Prairie du Chien-Jordan aquifer is small relative to the lateral flow and the base can be treated as a no-flow boundary.

6. Ground-water withdrawals from the drift and Platteville aquifer system are negligible and ground-water withdrawals from the underlying aquifers have a negligible effect on hydraulic heads in the drift and Platteville aquifer system.

Model Design

The C-C' cross-section (fig. 2) was chosen to represent the drift and Platteville aquifer system and to investigate hydrologic concepts of flow using the numerical model. The trace of the section is aligned with the major horizontal flow path. There are no significant horizontal flows tangent to the simulated flow path. Hydraulic heads and ground-water flow along the cross-section were simulated by the numerical model using 1 row and 91 columns (fig 13). The numerical model along the cross-section requires only one row because a vertical slice through the system, rather than the entire three-dimensional system, is simulated. The dimensions of each grid cell are 100 ft by 100 ft. The model was subdivided vertically into 8 layers, each corresponding to a horizontal hydrogeologic unit. The amount of geologic and hydraulic-head information available for the drift and Platteville aquifer system was insufficient for a more detailed vertical grid.

FIGURE 13.--NEAR HERE.

Figure 13.--Diagram showing hydrogeologic units and cross-section model layers

The thickness of a cell representing an aquifer unit is incorporated in the transmissivity term for the cell. Transmissivity is the product of the hydraulic conductivity and the saturated thickness. Hydraulic conductivity and transmissivity are measures of the ability of an aquifer to transmit water. Transmissivity of an unconfined aquifer can vary with changes in the saturated thickness of the aquifer, whereas the transmissivity of a confined aquifer is constant with time because the saturated thickness of the aquifer does not change.

The center of a grid cell, referred to as a node, represents the location for which the hydraulic head is computed by the cross-section model. Aquifer properties and stresses are assigned to the cells and are assumed to represent mean conditions within grid cells. Specific nodes and cells are referenced by citing row (i), column (j), and layer (k). The row number (i) is always 1 for the cross-section model because there is only one row in the model grid.

The cross-section model contains eight layers that represent, in descending order (1) the upper drift aquifer, (2) the upper drift confining unit, (3) the middle drift aquifer, (4) the lower drift confining unit, (5) the lower drift aquifer, (6) the Platteville aquifer, (7) the St. Peter aquifer, and (8) the Prairie du Chien-Jordan aquifer (fig. 13). The model layer representing the Prairie du Chien-Jordan aquifer was included to extend the model down vertically to an impermeable (no-flow) boundary. The model layer representing the lower drift aquifer includes till and sandy till (low permeability material), where these materials directly overlie the Platteville aquifer and sand and gravel deposits are absent. The model layer representing the Platteville aquifer includes sandy till in the bedrock valley (columns 63 to 72) where the Platteville aquifer is absent. The Glenwood Shale and basal St. Peter confining units are represented in the model by leakage terms that incorporate the thickness and vertical hydraulic conductivity of the unit in each model cell.

The transmissivities of the upper drift aquifer vary as the saturated thickness of the unit varies. The transmissivities of the lower drift confining unit, the lower drift aquifer, the Platteville aquifer, the St. Peter aquifer, and the Prairie du Chien-Jordan aquifer are constant in time for any individual model cell. The units are under confined conditions so their saturated thicknesses do not vary. The upper drift confining unit and middle drift aquifer are confined along most of the cross-section, but are unconfined near the eastern boundary where the overlying hydrogeologic units are absent. The transmissivities of these units vary in cells in which the units are under unconfined conditions and are constant in time in cells in which the units are under confined conditions.

Leakage of water between model layers is dependent on the thicknesses and vertical hydraulic conductivities of adjacent layers and the hydraulic head difference between adjacent layers. The Glenwood Shale confining unit, underlying the Platteville aquifer, and the basal St. Peter confining unit, underlying the St. Peter aquifer, are not represented as layers in the cross-section model. Ground-water flow in these confining units is predominantly vertical, with no significant horizontal component of flow. The assumption is made that these confining units make no measurable contribution to the horizontal conductance of the overlying and underlying layers. In each case, the confining unit is treated simply as the vertical conductance between the overlying and underlying aquifers. This formulation for the treatment of confining units is frequently referred to as the quasi-three-dimensional approach (McDonald and Harbaugh, 1988). A more detailed discussion of leakage of water between model layers is given in the Supplemental Information Section at the end of this report. The volume of water that moves vertically through the base of the Prairie du Chien-Jordan aquifer is considered small, relative to lateral flow in that aquifer, and its base is treated as a no-flow boundary.

Recharge to the upper drift aquifer occurs by percolation of precipitation to the water table and is represented in the cross-section model by a specified-flux boundary. For columns 61-80 the sand and gravel deposits overlying the upper drift confining unit are not represented in the model (and are not shown in fig. 13) because they are unsaturated. The simulated recharge in these columns (61-80) is applied directly to the upper drift confining unit. Simulated recharge is applied to the middle drift aquifer in areas where the upper drift aquifer and confining unit are absent and the middle drift aquifer is under water-table conditions (columns 81-91). The simulated recharge to the drift and Platteville aquifer system from precipitation represents the net difference between precipitation and evapotranspiration losses. Evapotranspiration losses include those occurring above the water table in the unsaturated zone and ground-water evapotranspiration losses.

The lower (vertical) boundary in the cross-section model is the base of the Prairie du Chien-Jordan aquifer. The base of the Prairie du Chien-Jordan aquifer is a no-flow boundary because it is underlain by the St. Lawrence-Franconia confining unit. The hydrogeologic units lying stratigraphically below the St. Lawrence-Franconia confining unit are thought to be in poor hydraulic connection with overlying units (Stark and Hult, 1985). The St. Lawrence-Franconia unit is a regional confining bed with a vertical hydraulic conductivity as little as 0.00007 ft/d (Schoenberg, 1990). Some vertical leakage of water from the base of the Prairie du Chien-Jordan aquifer through the St. Lawrence-Franconia confining bed undoubtedly does occur. In the model, losses due to downward leakage of water through the bottom of the Prairie du Chien-Jordan aquifer are not simulated. These potential losses though not considered significant, could result in recharge to the drift and Platteville aquifer system to be underestimated in the model. Model sensitivity analysis, however, indicated that variations in the hydraulic properties and boundary conditions of the Prairie du Chien-Jordan aquifer model layer had no significant effect on hydraulic heads and ground-water flow in the drift and Platteville aquifer system.

The particle-tracking post-processing program used to calculate path lines requires that hydraulic properties and hydrologic conditions be specified, in addition to those needed for the U.S. Geological Survey modular model (Pollock, 1989). The porosity, defined as the ratio of the volume of interstices (voids) to the total volume of a rock or soil, must be specified for each cell. Recharge may be assigned to the top face of a cell or treated as a distributed source. Simulated recharge was assigned to the top face of cells for the particle- tracking results discussed in this report.

In the numerical cross-section model, when a particle of water enters the simulated ground-water-flow system, it moves through the system until it reaches a boundary where flow is out of the system, or until it enters a cell containing an internal sink, such as a stream. Three options that can be used for modeling particle movements are (1) stopping particles when they enter cells that have any amount of discharge to internal sinks; (2) letting particles pass through cells for which only part of the water flowing into the cell discharges to the sink (weak sink cells), so that they discharge only at discharge boundaries or cells for which flow is into the cell from all directions (strong sink cells); or (3) stopping particles when they enter cells in which discharge to sinks is larger than a specified fraction of the total inflow of the cells. The option of letting particles pass through cells with weak sinks was used for the particle-tracking results discussed in this report. It should be noted, however, that no internal sinks are present along the cross-section model.

Boundary Conditions

Ideally, all model boundaries should represent the physical limits of the aquifer system or at other hydrogeologic boundaries, such as a river. Practical considerations, such as limitations affecting the size of the area modeled, however, often necessitate the use of arbitrarily imposed model boundaries that are within the natural hydrologic boundaries. The natural hydrologic boundaries of the upper drift (western boundary), middle drift, Platteville, St. Peter, and Prairie du Chien-Jordan aquifers lie beyond the modeled transect. A specified-head boundary, incorporating measured hydraulic heads in the aquifers, was used for these model layers (fig. 13). The measured hydraulic heads allow a reasonable representation of hydraulic conditions at the model boundaries, assuming the model-computed fluxes through the boundaries are reasonable. The use of specified-head boundaries is appropriate for this model because ground-water withdrawals have a negligible effect on the drift and Platteville aquifer system and the cross-section model is intended to be used for steady-state conditions.

No-flow boundaries (fig. 13) were used for the eastern boundary of the upper drift aquifer (model layer 1) and for both the eastern and western boundaries of the upper drift confining unit (model layer 2), the lower drift confining unit (model layer 4), and the lower drift aquifer (model layer 5). The eastern boundary of the upper drift aquifer is at the point where the aquifer becomes unsaturated (fig. 12) and, therefore, the flux across this boundary is zero. Because flow in the upper and lower drift confining units predominantly is vertically downward (fig. 12), flux across the model boundaries is negligible. The geologic material near the eastern and western boundaries of model layer 5, representing the lower drift aquifer, is till and sandy till. Model layer 5, representing the lower drift aquifer, is, in effect, a continuation of the overlying lower drift confining unit in areas where the lower drift aquifer is absent. Flow near both the eastern and western boundaries is predominantly vertical; therefore, flux across the model boundaries is negligible.

Alternative boundary conditions that could have been used for model layers with a specified-head boundary include a specified-flux or a general-head boundary condition (McDonald and Harbough, 1988). A specified-flux boundary was not used because (1) hydraulic heads in the aquifer units were known, (2) the cross-section model was intended to be used for steady-state conditions only (therefore, hydraulic heads at the boundaries are constant), and (3) the flux across the boundary is not well known due to limited data. A general-head boundary was not used because of uncertainty regarding the physical extent and continuity of the drift aquifer units beyond the boundaries of the cross-section.

Model Calibration

Model calibration is the process in which initial estimates of aquifer properties and boundary conditions are adjusted until calculated hydraulic heads and simulated ground-water flows adequately match measured water levels and flows. Because independent or field-determined estimates of ground-water flow along the cross-section are not available, the cross-section model was calibrated by matching simulated and measured hydraulic heads only. Model-computed flows, however, were compared with reasonable estimates of flow based on known ranges of hydraulic properties for the hydrogeologic units. Calibration and evaluation of the model was conducted for steady-state (equilibrium) conditions for a winter period, when ground-water withdrawals in the Twin Cities Metropolitan Area are smallest (on a seasonal basis). No storage terms or ground-water withdrawals are included in the steady-state simulation. Under steady-state conditions, the amount of water entering the aquifer system equals the amount of water leaving the aquifer system, and the long-term change in storage is zero.

Measured hydraulic heads in the drift and Platteville aquifer system during December, 1987, were used to define boundary conditions and calibrate the cross-section model. Water-level measurements were available from 24 wells located along the selected cross-section. The wells were completed in the upper drift (3 wells), middle drift (10 wells), lower drift (3 wells), Platteville (6 wells), and St. Peter (2 wells) aquifers (fig. 12).

During the winter season, the effect of ground-water withdrawals from the underlying St. Peter and Prairie du Chien-Jordan aquifers on hydraulic heads in the drift and Platteville aquifer system is considered minimal. Hydraulic heads in the St. Peter and Prairie du Chien-Jordan aquifers rebound and quickly approach steady-state conditions following the lessening of ground-water withdrawals in the late summer and fall. Schoenberg (1984) reported that hydraulic heads in the Prairie du Chien-Jordan aquifer changed less than 5 ft in most of the Twin Cities Metropolitan Area from 1971-80 and that, despite large ground-water withdrawals, no large cones of depression developed in the potentiometric surface. The winter steady-state potentiometric surfaces in all aquifers represented in the cross-section model have a northwest-to-southeast gradient along the cross-section, with no significant components of flow tangent to the trace of the cross-section.

The initial values of hydrologic properties used in the cross-section model are listed in table 2. The initial values for horizontal and vertical hydraulic conductivities of the hydrogeologic units in the cross-section model were based on: (1) reported values from within the study area, (2) Twin Cities Metropolitan Area values reported by Norvitch and others (1974), and (3) grain-size and lithologic descriptions from test-holes and well logs in the study area based on relationship between grain size class and hydraulic conductivity report by Koch (1980 p. 15). The initial value of recharge to the drift and Platteville aquifer system from infiltration of precipitation, 5.5 in/yr, was based on simulated leakage to the St. Peter aquifer in the St. Louis Park area during the 1970's reported by Stark and Hult (1985). Recharge to the drift and Platteville aquifer system initially was assumed to be similar to leakage to the St. Peter aquifer from overlying deposits. The initial values for porosity of the hydrogeologic units, used in the particle-tracking path line calculation (Pollock, 1989), were derived from mean values reported by Morris and Johnson (1967) and Freeze and Cherry (1979).

TABLE 2.--NEAR HERE.

Table 2.--Initial and calibrated values of hydraulic properties and fluxes used in cross-section model
[ft/d, feet per day; ft^2/d, feet squared per day; in/yr, inches per year; --, not applicable;
K_z, vertical hydraulic conductivity; K_x, horizontal hydraulic conductivity]

Hydrogeologic unit	Horizontal hydraulic conductivity (ft/d)	Saturated thickness (feet)	Transmissivity (ft^2/d)	Vertical hydraulic conductivity (ft/d)	Anisotropy (k_z/K_x)	Recharge (in/yr)	Porosity (percent)
Upper drift aquifer							
Peat	2.0	0-25	0-25	--	0.1	[1]6.0, 5.5	90
Sand and Gravel	50-400	0-25	0-10,000	--	.01	[1]6.0, 5.5	40
Upper drift confining unit	10-30	0-20	0-500	0.01 -0.04	--	[1]6.0, 5.5	35
Middle drift aquifer	50-500	15-25	1,000-12,500	--	.1	[1]6.0, 5.5	40
Lower drift confining unit	10-40	2-45	20-1,800	.0002 - .2	--	--	35
Lower drift aquifer	100-400	0-20	0-5,000	--	.1	--	32-40
Platteville aquifer	275	0-25	0-6875	--	.1	--	26
Glenwood shale confining unit	--	0-5	--	.00001	--	--	5
St. Peter aquifer	[1]25, 20	125	[1]3,125; 2,500	--	--	--	25
Basal St. Peter confining unit	--	0-20	--	[1].00002, .0009	--	--	5
Prairie du Chien-Jordan aquifer	55	200	11,000	--	--	--	31

[1] Calibrated value is...

The cross-section model was calibrated by systematically adjusting the values of horizontal and vertical hydraulic conductivities of the hydrogeologic units and the amount of recharge until calculated hydraulic heads acceptably matched measured water levels in wells along the cross-section. A difference of 0.2 ft or less between calculated and measured hydraulic heads was considered an acceptable match. The match between calculated hydraulic heads and measured water levels was improved by (1) adjusting the vertical hydraulic conductivities of the drift confining units within reported ranges, (2) decreasing the vertical hydraulic conductivity of the basal St. Peter confining unit to 0.00002 ft/d, (3) increasing the horizontal hydraulic conductivity of the St. Peter aquifer to 25 ft/d, and (4) increasing recharge to 6.0 in/yr. Model-computed vertical hydraulic conductivities for both the upper and lower drift confining units ranged from 0.0002 to 0.2 ft/d. The values of hydrologic properties resulting in the best fit between calculated hydraulic heads and measured water levels are listed in table 2 as calibrated value. A complete listing of the input data used in the cross-section model for the calibrated best-fit simulation is given in the Supplemental Information Section.

The best-fit calculated hydraulic heads generally were within 0.2 ft of measured water levels in wells along the cross-section. The differences greater than 0.2 ft were +0.3 ft for one well completed in the middle drift aquifer (cell 1, 70, 3), +0.4 ft for one well completed in the lower drift aquifer (cell 1, 46, 5), and +0.7 for one well completed in the Platteville aquifer (cell 1, 46, 6) (plus (+) indicates that the calculated hydraulic head was higher than the measured water level). The mean difference between calculated hydraulic heads and measured water levels, computed as the algebraic sum of the differences divided by the number of wells, was +0.06 ft, indicating the positive differences were approximately balanced by the negative differences. The mean difference between calculated hydraulic heads and measured water levels, computed as the sum of the absolute values of the differences divided by the number of wells, was 0.18 ft.

A number of factors contribute to the differences between calculated hydraulic heads and measured water levels. The calculated hydraulic heads, which represent mean, long-term steady-state conditions, were compared to hydraulic heads measured at a single point in time (December, 1987). Although the measured hydraulic heads approximated steady-state conditions, annual fluctuations in hydraulic heads do occur. Hydraulic heads measured at a single point in time probably do not precisely represent mean, long-term steady-state conditions. Other factors contributing to differences between calculated hydraulic heads and measured water levels include small-scale spatial variations in the hydraulic properties of the hydrogeologic units and observation wells not being located at the center of cross-section model cells.

Computed Water Budget And Flow

The computed water budget from the cross-section model is shown in table 3. Simulated recharge by precipitation to the uppermost model layers from infiltration accounts for about 41 percent of the total sources of water in the computed water budget, and boundary inflow from the west about 59 percent. About 66 percent of the simulated recharge enters the upper drift aquifer (model layer 1), about 23 percent enters the upper drift confining unit (model layer 2), and about 11 percent enters the middle drift aquifer (model layer 3) at the eastern end of the cross-section where the aquifer is unconfined. Boundary inflow to the middle drift aquifer accounts for nearly 32 percent of the total sources of water in the computed water budget. Boundary inflow to the upper drift aquifer accounts for about 13 percent of the total sources and boundary inflow to the bedrock aquifers (Platteville (model layer 6), St. Peter (model layer 7), and Prairie du Chien-Jordan (model layer 8)) about 15 percent. Recharge from infiltration of precipitation accounts for about 46 percent, boundary inflow to the middle drift aquifer about 36 percent, and boundary inflow to the upper drift and Platteville aquifers about 18 percent of the total sources of water to the drift and Platteville aquifer system (excluding the St. Peter and Prairie du Chien-Jordan aquifers).

TABLE 3.--NEAR HERE.

Table 3.--Computed water budget from cross-section model
[--, no source or discharge for a budget component]

Budget component	Source (cubic feet per second)	Percentage of total sources	Percentage of budget component	Percentage of total sources to model layers 1 to 6 (drift and Platteville aquifer system)	Discharge (cubic feet per second)	Percentage of total discharges
Simulated recharge						
Layer 1 (Upper drift aquifer)	0.0094	27.0	66.2	30.4	--	--
Layer 2 (Upper drift confining unit)	.0032	9.2	22.5	10.4	--	--
Layer 3 (Middle drift aquifer)	.0016	4.6	11.3	5.2	--	--
Subtotal	.0142	40.8	100.0	46.0	--	--
Specified head						
Layer 1 (Upper drift aquifer)	.0045	12.9	21.8	14.6	--	--
Layer 2 (Upper drift confining unit)	--	--	--	--	--	--
Layer 3 (Middle drift aquifer)	.0110	31.6	53.4	35.6	0.0073	21.0
Layer 4 (Lower drift confining unit)	--	--	--	--	--	--
Layer 5 (Lower drift aquifer)	--	--	--	--	--	--
Layer 6 (Platteville aquifer)	.0012	3.5	5.8	3.9	.0112	32.2
Subtotal	.0167	--	--	54.1	--	--
Layer 7 (St. Peter aquifer)	.0014	4.0	6.8	--	.0131	37.6
Layer 8 (Prairie du Chien-Jordan aquifer)	.0025	7.2	12.1	--	.0032	9.2
Subtotal	.0039	59.2	199.9	--	.0348	100.0
Total	.0348	100.0	--	[1]100.1	.0348	100.0

[1] Not 100.00 percent due to rounding error.

The only discharges in the computed water budget are boundary outflows from the eastern end of the cross-section model. About 70 percent of the boundary outflow occurs through the Platteville (model layer 6) and St. Peter (model layer 7) aquifers. Of the remaining 30 percent, about 21 percent occurs through the middle drift aquifer (model layer 3), and about 9 percent occurs through the Prairie du Chien-Jordan aquifer (model layer 8).

The general pattern of flow in the drift and Platteville aquifer system may be summarized as: (1) water entering the aquifer system by infiltration of precipitation and boundary inflow from the west, (2) water moving through the aquifer system horizontally to the east in the aquifers and vertically downward through the confining units, and (3) water discharging from the aquifer system by boundary outflow to the east through the middle drift and Platteville aquifers and by leakage downward to the St. Peter aquifer. Downward leakage of ground water through the lower boundary of the model layers in the drift and Platteville aquifer system is similar for each layer (table 4). However, leakage is somewhat greater through the lower boundary of the lower drift aquifer (model layer 5) and somewhat less through the lower boundary of the upper drift aquifer (model layer 1) than for the other aquifers. The lower drift aquifer is directly underlain by the Platteville aquifer along most of the cross-section, with no intervening confining unit, while the upper drift aquifer is underlain by the upper drift confining unit and is of lesser areal extent than the other aquifers.

TABLE 4.--NEAR HERE.

Table 4.--Computed leakage between model layers from cross-section model
[--, movement of water through the boundary was only downward, with no upward component of flow]

Leakage between model layers	Source (cubic feet per second)	Discharge (cubic feet per second)
Layer 1 (Upper drift aquifer)	0.0050	0.0189
Layer 2 (Upper drift confining Unit)		
Through upper boundary	.0189	.0050
Through lower boundary	.0052	.0223
Layer 3 (Middle drift aquifer)		
Through upper boundary	.0223	.0052
Through lower boundary	.0003	.0226
Layer 4 (Lower drift confining unit)		
Through upper boundary	.0226	.0003
Through lower boundary	.0000	.0224
Layer 5 (Lower drift aquifer)		
Through upper boundary	.0224	.0000
Through lower boundary	.0077	.0301
Layer 6 (Platteville aquifer)		
Through upper boundary	.0301	.0077
Through lower boundary	--	.0123
Layer 7 (St. Peter aquifer)		
Through upper boundary	.0123	--
Through lower boundary	--	.0007
Layer 8 (Prairie du Chien-Jordan aquifer)	.0007	--
	.1475	.1475

Discharge from the drift and Platteville aquifer system is by (1) leakage to the underlying St. Peter aquifer (model layer 7), about 40 percent; (2) boundary outflow from the Platteville aquifer (model layer 6), about 36 percent; and (3) boundary outflow from the middle drift aquifer (model layer 3), about 24 percent. The presence or absence of the Glenwood Shale confining unit strongly influences the amount of leakage from the drift and Platteville aquifer system to the underlying St. Peter aquifer. About 31 percent of the total leakage of water (through the lower boundary of the model layer representing the Platteville aquifer) to the St. Peter aquifer occurs through the bedrock valley in the eastern part of the cross-section model (columns 63 to 72, fig. 13) where the Platteville aquifer and Glenwood Shale confining unit are absent. West of the bedrock valley in columns 46 to 62, the Glenwood Shale confining unit is absent or discontinuous. About 99 percent of the total simulated leakage to the St. Peter aquifer occurs through the areas where the Glenwood Shale confining unit is absent or discontinuous (columns 46 to 72).

A particle-tracking post-processing program (Pollock, 1989) was used to compute ground-water-flow path lines based on output from the calibrated steady-state cross-section model. The results of the path-line calculations are graphically represented in figures 14 and 15. The path-line plot shown in figure 14 was generated with particles placed initially on the surface of the uppermost active model layer in columns 2 through 90 to represent the movement through the drift and Platteville aquifer system of recharge water derived from the infiltration of precipitation. Most of the recharge to the drift and Platteville aquifer system moves horizontally in the western part of the cross-section and discharges from the aquifer system by boundary outflow and downward leakage to the St. Peter aquifer (model layer 7) in the eastern part.

FIGURE 14.--NEAR HERE.

FIGURE 15.--NEAR HERE.

Figure 14.--Path-line plot representing movement through the drift and Platteville aquifer system of recharge water derived from the infiltration of precipitation

Figure 15.—Path-line plot representing movement through the drift and Platteville aquifer system of water derived from boundary inflow

The path-line plot shown in figure 15 was generated with particles placed initially on the left (inflow boundary) face of each model layer in column 1 to represent the movement through the drift and Platteville aquifer system of water derived from boundary inflow. The option of tracking particles forward in the direction of ground-water flow was used in both cases. Much of the water derived from boundary inflow discharges by downward leakage to the St. Peter aquifer (model layer 7) prior to reaching the bedrock valley. The predominant flow is initially horizontal within the aquifer units, but then becomes nearly vertical through the confining units. The vertical leakage of water through the lower drift confining unit (model layer 4) occurs mainly west of column 22 where the unit is only about 2-ft thick. The steep gradients of the path lines in the St. Peter aquifer, beginning in column 46, reflect the absence of the Glenwood Shale confining unit in columns 46 to 72. The greatly increased leakage to the St. Peter aquifer, because of the absence of the Glenwood Shale confining unit, probably results in an increased vertical hydraulic head gradient in the aquifer. No measured hydraulic heads for the St. Peter aquifer are available to verify the head gradient, except near the western edge of the discontinuity in the confining unit.

The path-line plots illustrate the major directions of flow in the drift and Platteville aquifer system as (1) predominantly horizontal flow in the aquifers, (2) predominantly vertical flow in the confining units, and (3) significant leakage of ground water from the drift and Platteville aquifer system to the underlying St. Peter aquifer (model layer 7) in the eastern part of the cross-section where the Glenwood Shale confining unit is absent. About 48 percent of the downward leakage of water through the lower drift confining unit (model layer 4) also occurs in the eastern part of the cross-section because the till and clay comprising the unit is sandier than it is in the western part. The vertical hydraulic conductivity of the lower drift confining unit is therefore greater in the eastern part.

Sensitivity Analyses

Changes in boundary conditions

The effects of using specified-head boundary conditions on calculated hydraulic heads and ground-water flow in the drift and Platteville aquifer system were investigated by substituting no-flow boundaries for specified-head boundaries and comparing the results. The changes in calculated hydraulic heads for each model layer that resulted from the substitution of no-flow boundaries for specified-head boundaries at the western boundary (where ground-water inflow to the drift and Platteville aquifer system occurs) are given in table 5.

TABLE 5.--NEAR HERE.

Table 5.--Sensitivity of calculated hydraulic heads to changes in cross-section model boundary conditions

[Mean deviation of hydraulic heads was calculated as the algebraic sum of the differences from the calibrated hydraulic heads for each variable-head cell divided by the number of cells. +, hydraulic heads for the sensitivity simulation greater than hydraulic heads for the calibrated simulation; -, hydraulic heads for the sensitivity simulation less than for the calibrated simulation; NA, not applicable, min., minimum; max., maximum]

	Deviation of hydraulic heads (feet)																	
	Layer 1			Layer 3			Layer 5			Layer 6			Layer 7			Layer 8		
Boundary condition	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean
No-flow western boundary for layer 1 (Upper drift aquifer)	-0.1	-1.8	-0.3	0.0	-0.2	-0.1	0.0	-0.2	-0.1	0.0	-0.2	-0.1	0.0	-0.1	<0.05	0.0	0.0	0.0
No-flow western boundary for layer 3 (Middle drift aquifer)	-.3	-1.3	-.9	.0	-2.7	-.8	-.2	-.9	-.6	.0	-.9	-.5	.0	-.4	-.2	.0	.0	.0
No-flow western boundary for layer 6 (Platteville aquifer)	.0	-.2	-.1	.0	-.2	-.1	.0	-.3	-.2	.0	-.5	-.2	.0	-.1	<.05	.0	.0	.0
No-flow western boundary for layer 7 (St. Peter aquifer)	.0	-.2	-.1	.0	-.2	-.1	.0	-.3	-.1	.0	-.3	-.1	.0	-2.4	-.9	.0	.0	.0
No-flow western boundary for layer 8 (Prairie du Chien-Jordan aquifer)	.0	-.1	<.05	.0	.0	.0	.0	-.1	<.05	.0	.0	.0	.0	-.1	<.05	.0	-1.7	-.9
No-flow western boundary for all layers	-7.6	[1]-14.2	NA	-.2	-14.1	-7.5	-2.2	-10.8	-6.9	-.1	-10.9	-6.5	-.2	-7.5	4.9	.0	-1.8	.9
East boundary of layer 5 (Lower drift aquifer), specified head	.0	.0	.0	.0	.0	.0	.0	-.1	<.05	.0	-.1	<.05	.0	.0	.0	.0	.0	.0

[1] 34 of 60 cells (57 percent) were dewatered.

Calculated hydraulic heads in the drift and Platteville aquifer system were most affected by changes in the boundary condition for the middle drift aquifer (model layer 3), with mean declines ranging from 0.5 to 0.9 ft. Mean declines in calculated hydraulic heads resulting from changes in the boundary conditions for the upper drift aquifer (model layer 1) and for the Platteville aquifer (model layer 6) were equal to or less than 0.3 ft in all model layers. The calculated hydraulic head declines for a given model layer were greatest near the western boundary of the cross-section model and generally decreased to almost zero near the eastern boundary of the model. Mean declines in calculated hydraulic heads in the drift and Platteville aquifer system resulting from changes in the boundary conditions for the underlying bedrock aquifers (St. Peter and Prairie du Chien-Jordan aquifers, model layers 7 and 8) were equal to or less than 0.1 ft. The simulations indicated that the type of boundary condition imposed at the western boundary of the cross-section model did not have a significant effect on hydraulic heads in the drift and Platteville aquifer system, except for changes in the type of boundary condition used for the middle drift aquifer.

The western cross-section model boundary was changed to a no-flow boundary for all the model layers, with recharge from precipitation as the only source of water. The change in boundary conditions resulted in 57 percent of the model layer cells representing the upper drift aquifer (model layer 1) becoming desaturated. Mean declines in calculated hydraulic heads in the other aquifer units ranged from 0.9 ft in the Prairie du Chien-Jordan aquifer (model layer 8) to 7.5 feet in the middle drift aquifer (model layer 3).

When the western boundary condition of a model aquifer layer was changed from a specified-head to a no-flow boundary the main effect on simulated ground-water flow was to increase the inflow through the western boundaries of the other layers representing aquifer units. Changing the western boundary of the middle drift aquifer (model layer 3) resulted in the greatest increases in boundary inflow to the other aquifers because ground-water inflow to the middle drift aquifer was much greater than to the other aquifers. Inflow was increased as much as 325 percent in the Platteville aquifer (model layer 6). Boundary outflow through the eastern boundary of an aquifer unit decreased by a small amount (about 7 percent or less) as a result of the imposed boundary condition change on the western boundary. Changing the western boundary condition of a model layer representing an aquifer also resulted in greater leakage of water down from overlying aquifer units (increases of about 10 to 25 percent). In summary, the volume of water lost to the aquifer system by eliminating boundary inflow to an aquifer unit was compensated for by (1) boundary inflow to the other aquifer units, and (2) to a lesser degree, reduced boundary outflow and increased leakage of water down from overlying aquifer units.

The effects of changing the eastern boundary of the lower drift aquifer (model layer 5) from a no-flow to a specified-head boundary on calculated hydraulic heads and simulated ground-water flow also were investigated (table 5). Driller's logs with sufficient detail of the lower drift confining unit and lower drift aquifer along the cross-section east of the bedrock valleys are not available. Consequently, sand and gravel units of the lower drift aquifer may overlie the Platteville aquifer in this area, resulting in a significant horizontal component of flow near this boundary. Changing the boundary condition from no-flow to a specified-head, however, resulted in no significant change in calculated hydraulic heads (0.1 ft or less). The resultant simulated boundary outflow for the lower drift aquifer (model layer 5) also was not significant in relation to total flow (about 0.0001 cubic feet per second), and leakage to the underlying Platteville aquifer (model layer 6) was reduced by less than 1 percent.

Changes in hydraulic properties and recharge

A model-sensitivity analysis, wherein the value of a single hydrologic property is varied while all other properties are held constant, was done to identify the relative effect of changes in hydraulic properties and recharge on calculated hydraulic heads and simulated ground-water flow. The degree to which the hydrologic properties can be adjusted is related to the uncertainty as to their correct or true value associated with each property. For example, the range of values reported in the literature for horizontal hydraulic conductivity of each aquifer unit is relatively small (about ± 2 times the initial values used in the model); therefore, the uncertainty as to the correct or true value is relatively small. In contrast, the confining units have a wide range in values reported in the literature of vertical hydraulic conductivities, spanning 2 or 3 orders of magnitude; therefore, the uncertainty as to their correct value is large. Variations of hydrologic properties were kept within reported or plausible ranges of values (table 6). Horizontal hydraulic conductivities and transmissivities of the model layers were varied by factors of 1.5 and 0.5. The vertical leakance terms controlling leakage between layers were varied by factors of 10 and 0.1. Variations in the vertical leakance terms correspond to variations in the vertical hydraulic conductivity of the confining units because the vertical hydraulic conductivities of the confining units are much smaller than the vertical hydraulic conductivities of the aquifers. Recharge was varied by factors of 1.333 and 0.667, which correspond to plus and minus 2.0 in/yr.

TABLE 6.--NEAR HERE.

Table 6.--Sensitivity of calculated hydraulic heads and fluxes to changes in values of hydraulic properties and recharge

[Mean deviation of hydraulic heads was calculated as the algebraic sum of the differences from the calibrated hydraulic heads for each variable-head cell divided by the number of cells. +, hydraulic heads for the sensitivity simulation greater than the calibrated simulation; -, hydraulic heads for the sensitivity simulation less than the calibrated simulation; NA, not applicable; min., minimum; max., maximum]

Hydraulic property or recharge	Multiplied by factor of	Deviation of calculated hydraulic heads (feet)																		Deviation from calibrated net flux across lower boundary (cubic feet per second)		
		Layer 1			Layer 3			Layer 5			Layer 6			Layer 7			Layer 8					
		min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	deviation	layer	percent change
Horizontal hydraulic conductivity of layer 1 (Upper drift aquifer)	1.5	-0.2	+0.7	+0.1	-0.2	+0.4	<0.05	-0.1	+0.2	<0.05	-0.1	+0.2	<0.05	0.0	+0.1	+0.1	0.0	0.0	0.0	+0.00073	1	16.1
Horizontal hydraulic conductivity of layer 1 (Upper drift aquifer)	.5	-1.0	+.3	-.1	-.5	+.3	<.05	-.3	+.1	-.1	-.3	+.1	-.1	-.2	.0	-.1	.0	.0	.0	-.00125	1	27.5
Horizontal hydraulic conductivity of layer 2 (Upper drift confining unit)	1.5	-.1	.0	<.05	-.1	+.1	<.05	.0	+.1	<.05	.0	+.1	<.05	0	+.1	<.05	.0	.0	.0	+.00014	1	3.1
																				-.00003	3	.7
Horizontal hydraulic conductivity of layer 2 (Upper drift confining unit)	.5	.0	+.1	<.05	-.1	+.1	<.05	-.1	.0	<.05	-.1	.0	<.05	-.1	.0	<.05	.0	.0	.0	-.00016	1	3.5
																				+.00004	3	1.1
Horizontal hydraulic conductivity of layer 3 (Middle drift aquifer)	1.5	.0	+.4	+.4	-.1	+.4	+.2	.0	+.3	+.2	.0	+.3	+.2	.0	+.2	+.1	.0	.0	.0	+.00195	3	52.8
Horizontal hydraulic conductivity of layer 3 (Middle drift aquifer)	.5	-.7	.0	-.4	-.7	+.2	-.3	-.5	.0	-.3	-.5	.0	-.3	-.3	.0	-.1	.0	.0	.0	-.00298	3	80.6
Transmissivity of layer 4 (Lower drift confining unit)	1.5	-.1	.0	<.05	-.1	+.1	<.05	-.1	+.3	<.05	-.1	+.1	<.05	-.1	.0	<.05	.0	.0	.0	-.00005	3	1.4
																				+.00001	6	.1
Transmissivity of layer 4 (Lower drift confining unit)	.5	.0	+.1	<.05	-.1	+.1	<.05	-.3	+.1	<.05	-.1	+.1	<.05	.0	+.1	<.05	.0	.0	.0	+.00006	3	1.6
																				+.0000003	6	.00833

Table 6.--Sensitivity of calculated hydraulic heads and fluxes to changes in values of hydraulic properties and recharge--Continued

Hydraulic property or recharge	Multi-plied by factor of	Deviation of calculated hydraulic heads (feet): Layer 1			Layer 3			Layer 5			Layer 6			Layer 7			Layer 8			Deviation from calibrated net flux across lower boundary (cubic feet per second)		
		min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	deviation	layer	percent change
Transmissivity of layer 5 (Lower drift aquifer)	1.5	-.1	+.1	<.05	-.1	+.2	<.05	-.2	+.4	<.05	-.2	+.2	<.05	-.1	+.1	<.05	.0	.0	.0	+.00003	6	.3
Transmissivity of layer 5 (Lower drift aquifer)	.5	-.1	+.1	<.05	-.2	+.1	<.05	-.5	+.3	-.1	-.3	+.2	<.05	-.1	.0	<.05	.0	.0	.0	-.00003	6	.3
Transmissivity of layer 6 (Platteville aquifer)	1.5	-.3	.0	-.2	-.3	.0	-.2	-.3	+.2	-.2	-.3	+.2	-.1	-.1	+.1	<.05	.0	.0	.0	-.00148	6	14.8
Transmissivity of layer 6 (Platteville aquifer)	.5	.0	+.4	+.3	.0	+.4	+.3	-.4	+.6	+.3	-.5	+.7	+.2	-.2	+.2	<.05	.0	.0	.0	+.00254	6	25.3
Transmissivity of layer 7 (St. Peter aquifer)	1.5	-.4	.0	-.2	-.5	.0	-.2	-.7	.0	-.3	-.7	.0	-.3	-1.1	.0	-.6	.0	-.0	.0	+.00155	6	15.5
																				-.002177	7	23.9
Transmissivity of layer 7 (St. Peter aquifer)	.5	.0	+.6	+.3	.0	+.7	+.3	.0	+1.0	+.5	.0	+1.0	+.5	.0	+1.6	+.9	.0	+.1	<.05	-.00240	6	23.9
																				+.00430	7	37.0
Transmissivity of layer 8 (Prairie du Chien-Jordan aquifer)	1.5	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	-.1	.0	<.05	0	7	0
																				-.0000002	8	.03
Transmissivity of layer 8 (Prairie du Chien-Jordan aquifer)	.5	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	+.1	<.05	.0000003	7	.003
																				+.0000005	8	.07
Vertical leakance term for layers 1 and 2	10.	-1.5	+0.1	-0.3	-0.1	+0.2	<.05	0.0	+0.1	<0.05	0.0	+0.1	<0.05	0.0	+0.1	<0.05	0.0	0.0	0.0	+0.0024	1	17.3
Vertical leakance term for layers 1 and 2	.1	-.1	+4.8	+1.0	-.4	+.3	-.1	-.3	.0	-.1	-.2	.0	-.1	-.2	.0	-.1	.0	.0	.0	-.0047	1	33.8
Vertical leakance term for layers 2 and 3	10.	-.3	.0	-.1	-.1	+.2	<.05	.0	+.1	<.05	.0	+.1	<.05	.0	+.1	<.05	.0	.0	.0	+.0015	2	8.9
Vertical leakance term for layers 2 and 3	.1	.0	+1.3	+.3	-.4	+.4	<.05	-.2	.0	-.1	-.2	.0	-.1	-.1	.0	-.1	.0	.0	.0	-.0029	2	17.0

Table 6.--Sensitivity of calculated hydraulic heads and fluxes to changes in values of hydraulic properties and recharge--Continued

Hydraulic property or recharge	Multiplied by factor of	Deviation of calculated hydraulic heads (feet)																		Deviation from calibrated net flux across lower boundary (cubic feet per second)		
		Layer 1			Layer 3			Layer 5			Layer 6			Layer 7			Layer 8					
		min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	deviation	layer	percent change
Vertical leakance term for layers 3 and 4	10.	-.7	.0	-.3	-.7	+.1	-.2	-.5	+.3	<.05	.0	+.3	+.1	.0	+.2	+.1	.0	.0	.0	+.0004	3	1.8
Vertical leakance term for layers 3 and 4	.1	.0	+1.8	+.8	.0	+1.8	+.9	-.9	-.3	-.7	-.9	.0	-.6	-.7	.0	-.4	.0	.0	.0	-.0056	3	25.1
Vertical leakance term for layers 4 and 5								.0	+.3	+.1	.0	+.2	+.1	.0	+.1	+.1	.0	.0	.0	+.0014	4	6.3
Vertical leakance term for layers 4 and 5	.1	.0	+1.5	+.8	+.1	+1.5	+.8	-.9	-.2	-.7	-.8	.0	-.6	-.7	.0	-.4	.0	.0	.0	-.0059	4	26.4
Vertical leakance term for layers 5 and 6	10.	-.3	.0	-.1	-.7	.0	-.2	-2.6	+.1	-.6	-.2	+.3	<.05	-.1	.0	<.05	.0	.0	.0	+.0021	5	9.4
Vertical leakance term for layers 5 and 6	.1	.0	+.6	+.3	+.1	+1.0	+.4	-.6	+2.0	+.6	-.9	+.2	-.1	-.3	.0	-.1	.0	.0	.0	-.0033	5	14.8
Vertical leakance term for layers 6 and 7	10.	-.4	.0	-.2	-.4	.0	-.2	-.5	-.1	-.3	-.6	.0	-.3	.0	+1.2	+.7	.0	.0	.0	+.0030	6	24.3
Vertical leakance term for layers 6 and 7	.1	.0	+1.1	+.5	.0	+1.2	+.5	+.2	+1.8	+.9	.0	+1.8	+.8	-3.7	-.1	-2.1	.0	.0	.0	-.0075	6	60.8
Vertical leakance term for layers 7 and 8	10.	-.3	.0	-.1	-.4	.0	-.2	-.6	.0	-.3	-.6	.0	-.2	-1.2	-.1	-.7	.0	+.6	+.4	+.0064	7	884.0
Vertical leakance term for layers 7 and 8	.1	.0	+.1	<.05	.0	+.1	<.05	.0	+.1	<.05	.0	+.1	<.05	.0	+.2	+.1	-.1	.0	<.05	-.0007	7	90.0
Recharge to uppermost active layer	1.333	.0	+.7	+.4	.0	+.6	+.35	.0	+.3	+.25	.8	+.3	+.2	.0	+.2	+.1	.0	.0	.0	NA		
Recharge to uppermost active layer	.667	-.8	.0	-.4	-.6	.0	-.35	-.4	.0	-.25	-.3	.0	-.2	-.3	.0	-.1	.0	.0	.0	NA		

The sensitivity analyses indicate that calculated hydraulic heads in the drift and Platteville aquifer system were most sensitive to variations in (1) horizontal hydraulic conductivities of the middle drift aquifer, (2) transmissivities of the Platteville and St. Peter aquifers, (3) vertical hydraulic conductivities of the lower drift confining unit, (4) vertical hydraulic conductivity of drift material filling the bedrock valley where the Platteville aquifer and Glenwood Shale confining unit are absent, (5) vertical hydraulic conductivity of the basal St. Peter confining unit, and (6) recharge. Varying the horizontal hydraulic conductivities of the middle drift aquifer (model layer 3) or the transmissivities of the Platteville aquifer (model layer 6) or the St. Peter aquifer (model layer 7) by factors of 1.5 and 0.5 resulted in mean differences in calculated hydraulic heads in the drift and Platteville aquifer system of 0.1 to 0.5 ft (table 6), with a range in differences from0 to 1.0 ft. Variations in the horizontal hydraulic conductivities of the upper drift aquifer (model layer 1), the upper drift confining unit (model layer 2), the lower drift confining unit (model layer 4), the lower drift aquifer (model layer 5), or the Prairie du Chien-Jordan aquifer (model layer 8) resulted in mean differences in calculated hydraulic heads of 0.1 ft or less (table 6).

The general effect of increasing the hydraulic conductivities of the upper drift aquifer (model layer 1) or the transmissivities of the middle drift aquifer (model layer 3) was to increase the net boundary flow (boundary inflow minus boundary outflow) to the aquifers by about 16 and 53 percent (table 6), respectively, thereby resulting in higher calculated hydraulic heads in the model. The general effect of increasing the transmissivities of the Platteville aquifer (model layer 6) or the St. Peter aquifer (model layer 7) was to decrease the net boundary flow to the aquifers (by increasing the boundary outflow) by about 15 and 24 percent (table 6), respectively, thereby resulting in lower calculated hydraulic heads in the model. The general effect of decreasing the hydraulic conductivities or transmissivities of the aquifer units (varying only one hydrologic property for one model layer at a time) was to decrease the net boundary flow, with a net loss in flow of 28 and 81 percent to the aquifer, for the upper drift and middle drift aquifers, respectively. Net boundary flow was increased, with a net gain in flow of 25 and 37 percent to the aquifer, for the Platteville and St. Peter aquifers, respectively.

Calculated hydraulic heads in the drift and Platteville aquifer system were significantly affected by varying the vertical hydraulic conductivities of the upper drift confining unit or the lower drift confining unit or the drift material filling the bedrock valley by factors of 10 and 0.1. Increasing the vertical hydraulic conductivity of the basal St. Peter confining unit by a factor of 10 also significantly affected calculated hydraulic heads. Mean differences in calculated hydraulic heads for the aquifers varied from less than 0.05 to 1.0 ft, with a range in differences from 0.0 to 4.8 ft (table 6). The largest calculated differences occurred in the upper drift aquifer and in the eastern part of the cross-section near the bedrock valley. Decreasing the vertical hydraulic conductivity by a factor of 10 generally resulted in much larger deviations from the calibrated best-fit hydraulic heads than did increasing the vertical hydraulic conductivity by a factor of 10. The general effect of increasing the vertical hydraulic conductivity of a confining unit (that is, increasing the vertical leakance term for adjacent layers) was to lower calculated hydraulic heads in the aquifers above the confining unit and to raise calculated hydraulic heads in the aquifers below the confining unit. The general affect of decreasing the vertical hydraulic conductivity of a confining unit was to raise calculated hydraulic heads in the aquifers above the confining unit and to lower calculated heads in the aquifers below the confining unit.

The percentage increase in net flux across the lower boundary of an aquifer from the calibrated best-fit simulation resulting from increasing the vertical hydraulic conductivity of an adjacent confining unit ranged from about 2 percent for the middle drift aquifer (model layer 3) to about 884 percent (nearly 9 times the calibrated best-fit value) for the St. Peter aquifer (model layer 7) (table 6). The percentage increase for the St. Peter aquifer is large because the net flux across the underlying basal St. Peter confining unit for the calibrated best fit simulation was small, only about 0.05 times the net flux across the lower boundary of the other aquifers, due to the low vertical hydraulic conductivity of the confining unit. The effect of the increased flow across the lower boundary of the St. Peter aquifer on hydraulic heads in the drift and Platteville aquifer system is small, resulting in changes in hydraulic heads of 0.3 ft or less. The percentage decrease in net flux across the lower boundary of an aquifer that resulted from decreasing the vertical hydraulic conductivity of a confining unit ranged from about 15 percent for the lower drift aquifer (model layer 5) to about 90 percent for the St. Peter aquifer (model layer 7). The largest changes in net flux across the lower boundary of the lower drift and Platteville (model layer 6) aquifers resulting from variations in vertical leakance terms occur in and near the bedrock valley.

The sensitivity analysis indicated the cross-section model steady-state hydraulic heads were relatively insensitive to large variations in the hydraulic properties of the hydrogeologic units. The imposed variations, however, did have a significant effect on simulated ground-water flow in the drift and Platteville aquifer system. Varying the vertical hydraulic conductivities of the confining units, in particular, had significant effects on ground-water flow, and therefore migration of contaminants, in the aquifer system. The implications of the results of the model analysis for migration of contaminants is discussed later in the report. The results of the sensitivity analysis indicate that the most important additional information needed to better simulate the drift and Platteville aquifer system in the study area is an improved definition, in terms of extent and hydraulic properties, of the confining units.

Varying recharge to the drift and Platteville aquifer system (applied to the uppermost active model layer) by factors of 1.333 and 0.667 ($\pm$ 2.0 in/yr) resulted in mean differences in calculated hydraulic heads of 0.2 to 0.4 ft, with a range in differences from 0.0 to 0.8 ft (table 6). The sensitivity of calculated hydraulic heads, in the cross-section model, to variations in recharge is lessened by the influence of the specified-head boundaries for the aquifer units. Ground-water inflow from the west is a significant source of water to the aquifer system in the study area, about 59 percent based on the computed water budget from the cross-section model.

Hypothetical Hydrologic Conditions

The calibrated steady-state cross-section model was used to investigate the effects of varying the hydraulic properties of confining units and the physical extent of the Glenwood Shale confining unit on calculated hydraulic heads and simulated ground-water flow in the drift and Platteville aquifer system. The variations included (1) increasing the vertical hydraulic conductivity of the lower drift confining unit (model layer 4) by a factor of 100 in the western part (columns 1 to 60) of the cross-section, (2) making the Glenwood Shale confining unit continuous in the area west of the bedrock valley (columns 46 to 62), (3) making the Glenwood Shale confining unit continuous across the bedrock valley (columns 63 to 72), and (4) making the Glenwood Shale confining unit continuous along the entire cross-section. The distribution and hydraulic properties of confining units are of major importance to ground-water flow and the potential transport of contaminants near the plant site.

In the simulations of hypothetical hydrologic conditions, the hydraulic properties and physical extent of the confining units that most affected ground-water flow were varied; these units are the lower drift (model layer 4) and Glenwood Shale confining units. The effects of increased vertical leakage preferentially in the wester part of the cross-section and the effects of changes in the location and extent of the bedrock valley on hydraulic heads and ground-water flow were evaluated. The simulations (1) provide a better understanding of the role of confining units in the ground-water-flow system, and (2) illustrate the effects of possible errors in representing the drift and Platteville aquifer system due to uncertainty regarding the extent of the Glenwood Shale confining unit.

The vertical hydraulic conductivity of the lower drift confining unit (model layer 4, columns 1-60) was increased by a factor of 100 in the western part of the cross-section. This resulted in a mean deviation from the calculated hydraulic heads from the calibrated best-fit simulation of (1) -0.8 ft and -0.5 ft in the overlying upper drift aquifer (model layer 1) and middle drift aquifer (model layer 3), respectively; and (2) in the underlying lower drift (model layer 5), Platteville (model layer 6), and St. Peter (model layer 7) aquifers, the mean deviations ranged from +0.4 to +0.6 ft (table 7).

TABLE 7.--NEAR HERE.

Table 7.--Changes in hydraulic heads because of hypothetical changes in confining unit properties

[Average deviation of hydraulic heads calculated as the algebraic sum of the differences from the calibrated hydraulic heads for each variable-head cell divided by the number of cells. +, deviation hydraulic heads for the sensitivity simulation greater than the calibrated simulation; -, deviation indicates hydraulic heads for the sensitivity simulation less than for the calibrated simulation; NA, not applicable; min., minimum; max., maximum]

		Deviation of hydraulic heads (feet)																	
	Multiplied	Layer 1			Layer 3			Layer 5			Layer 6			Layer 7			Layer 8		
Confining unit property	by factor of	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean
Vertical leakance term for layers 3 and 4 and layers 4 and 5 in western part of cross-section (columns 1-60)	100	-1.9	0.0	-0.8	-1.9	+0.1	-0.5	0.0	+2.3	+0.6	0.0	+1.4	+0.4	0.0	+0.9	+0.4	0.0	0.0	0.0
Glenwood Shale confining unit continuous west of bedrock valley (columns 46-62)	NA	.0	+.7	+.4	.0	+.7	+.3	.0	+1.7	+.7	.0	+1.7	+.6	-3.1	-.1	-1.5	.0	.0	.0
Glenwood shale confining unit continuous across bedrock valley (columns 63-72)	NA	.0	+.2	<.05	.0	+.3	+.1	.0	+.3	+.1	.0	+.5	+.1	-.9	.0	-.3	.0	.0	.0
Glenwood shale confining unit continuous across the bedrock valley and the area west of the bedrock valley (columns 46-72)	NA	.0	+1.6	+.7	+.1	+1.8	+.8	+.1	+2.8	1.3	.0	+2.8	+1.3	-6.0	-.2	-3.4	-.1	.0	.0

As a result of increasing the vertical hydraulic conductivity of the lower drift confining unit by a factor of 100 in the western part of the cross-section, the net boundary flow for the middle drift aquifer (model layer 3) increased by about 59 percent (table 8). The hydraulic gradient in the middle drift aquifer at the western boundary increased and boundary inflow increased by 20 percent. The net boundary flow for the Platteville aquifer (model layer 6) decreased by about 11 percent. The hydraulic gradient in the Platteville aquifer at the western boundary decreased because of greater leakage through the overlying confining unit and boundary inflow decreased by 48 percent. The net flux across the lower boundary of the lower drift confining unit (model layer 4) increased by about 11 percent. The leakage of water from the drift and Platteville aquifer system (model layers 1 to 6) to the underlying St. Peter aquifer (model layer 7) through the bedrock valley (columns 63 to 72) decreased by about 10 percent. This indicates that increased vertical leakage of water through the drift and Platteville aquifer system in the western part of the cross-section results in (1) increased leakage to the St. Peter aquifer in the western part of the cross-section, and (2) decreased leakage to the St. Peter aquifer through the bedrock valley. A widening of the area of vertical leakage through the lower drift confining unit (model layer 4) to the west to include columns 59 to 63 is apparent when compared to figure 14 for the calibrated best-fit simulation.

TABLE 8.--NEAR HERE.

FIGURE 16.--NEAR HERE.

Table 8.--Changes in fluxes because of hypothetical changes in confining unit properties
[+, net gain in flux and a percentage increase; -, net loss in flux and a percentage decrease]

Change in confining unit property or extent	Deviation from calibrated net boundary flux (cubic feet per second)			Deviation from calibrated net flux across lower boundary (cubic feet per second)			Deviation from calibrated flux through bedrock valley (columns 63-72) (cubic feet per second)	
	deviation	layer	percent change	deviation	layer	percent change	deviation	layer
Vertical leakance term increased by a factor of 100 for layers 3 and 4 and layers 4 and 5 in western part of cross-section (columns 1-60)	+0.00219 -.00106	3 6	+59.3 -10.6	+0.0025 +.0025 +.0014	3 4 6	+11.2 +11.2 +11.4	-0.000381	-10.0
Glenwood Shale confining unit made continuous west of bedrock valley (columns 46-62)	-.00037 -.00182 +.00429	5 6 7	[1]-- -18.2 +37.0	-.0043	6	-34.9	+.004119	+108.4
Glenwood shale confining unit made continuous across bedrock valley (columns 63-72)	-.00032 -.00094 +.00172	5 6 7	[1]-- -9.4 +14.8	-.0017	6	-13.8	-.003794	-99.8
Glenwood shale confining unit made continuous across the bedrock valley and the area west of the bedrock valley (columns 46-72)	-.00108 -.00489 +.01212	5 6 7	[1]-- -48.8 +104.4	-.0121	6	-98.1	-.003781	-99.5

[1] Indicates not applicable because boundaries for layer 5 in the calibrated simulation were zero-flux (no-flow) boundaries.

Figure 16.–Path-line plot representing movement through the drift and Platteville aquifer system of recharge water derived from the infiltration of precipitation with the vertical hydraulic conductivity of the lower drift confining unit increased by a factor of 100 in the western part of the modeled cross-section

The effect of varying the areal extent of the Glenwood Shale confining unit and the bedrock valley on calculated hydraulic heads and simulated ground-water flow in the drift and Platteville aquifer system was investigated. This was done by varying the representation of the areal extent of the Glenwood Shale confining unit in the cross-section model. The Glenwood Shale confining unit is absent in an area immediately to the west of and through the bedrock valley, allowing the Platteville aquifer to directly overlie the St. Peter aquifer. In the model the Glenwood Shale confining unit is not represented in columns 46 to 72. A hypothetical extension of the confining unit was simulated by decreasing the vertical hydraulic conductivity used in the vertical leakance term calculation for model layers 6 and 7 to .00001 ft/d in columns 46 to 62. The same hydrologic conditions at the eastern cross-section model boundary were imposed as for the calibrated best-fit simulation. A specified-head boundary condition was used for the eastern boundaries of the lower drift confining unit and the lower drift aquifer (model layers 4 and 5, respectively) and specified-head values corresponding to the calibrated best-fit hydraulic heads were used. Simulating a hypothetical extension of the Glenwood Shale confining unit west of the bedrock valley resulted in mean rises in calculated hydraulic heads in the drift and Platteville aquifer system (model layers 1-6) ranging from 0.3 ft in the middle drift aquifer (model layer 3) to 0.7 ft in the lower drift aquifer (table 7). Calculated hydraulic heads in the St. Peter aquifer were 0.1 to 3.1 ft lower, with the mean decrease for the aquifer being 1.5 ft.

As a result of simulating a hypothetical extension of the Glenwood Shale confining unit in columns 46 to 62, the net boundary flow for the Platteville aquifer (model layer 6) decreased by about 18 percent (table 8). Boundary outflow from the Platteville aquifer increased by 5 percent due to about a 35 percent reduction in the amount of water leaking to the underlying St. Peter aquifer (model layer 7). The net boundary flow for the St. Peter aquifer increased by about 37 percent. Boundary outflow from the St. Peter aquifer decreased by 15 percent. The amount of water leaking from the drift and Platteville aquifer system (model layers 1-6) to the St. Peter aquifer through the bedrock valley more than doubled (increased by about 108 percent, table 6), even though the total amount of water leaking from the drift and Platteville aquifer system to the St. Peter aquifer decreased by about 35 percent. The additional water leaking to the underlying St. Peter aquifer through the bedrock valley was derived from water that was impeded from leaking downward west of the bedrock valley by the simulated extension of the Glenwood Shale confining unit.

A second hypothetical variation of the extent of the Glenwood Shale confining unit was simulated. In this simulation the vertical hydraulic conductivity used in the vertical leakance term calculation for model layers 6 and 7 was decreased to .00001 ft/d in columns 63 to 72. In effect, the Glenwood Shale confining unit was modeled as underlying the bedrock valley. This simulation resulted in mean rises in calculated hydraulic heads in the drift and Platteville aquifer system (model layers 1-6) of about 0.1 ft, with deviations from calibrated best-fit hydraulic heads ranging from 0 to 0.5 ft (table 7). Calculated hydraulic heads in the St. Peter aquifer (model layer 7) were 0 to 0.9 ft lower, with the mean decrease for the aquifer being 0.3 ft.

As a result of simulating a hypothetical extension of the Glenwood Shale confining unit in columns 63 to 72, the net boundary flow for the Platteville aquifer (model layer 6) decreased by about 9 percent (table 8). Boundary outflow from the Platteville aquifer increased by 8 percent, primarily due to about a 14 percent reduction in the amount of water leaking to the underlying St. Peter aquifer (model layer 7). The leakage of water from the drift and Platteville aquifer system (model layers 1-6) to the St. Peter aquifer that was calculated as occurring through the bedrock valley was greatly reduced (decreased by 99.8 percent, table 8). As a result, the water that was impeded from leaking downward through the bedrock valley discharged from the drift and Platteville aquifer system by boundary outflow. Net boundary flow for the St. Peter aquifer increased by about 15 percent, and boundary outflow from the St. Peter aquifer decreased by 12 percent.

A third hypothetical variation of the extent of the Glenwood Shale confining unit was simulated by decreasing the vertical hydraulic conductivity used in the vertical leakance term calculation for model layers 6 and 7 to 0.00001 ft/d in columns 46 to 72; this, in effect, made the Glenwood Shale confining unit continuous along the entire cross-section. This simulation resulted in mean rises in calculated hydraulic heads in the drift and Platteville aquifer system ranging from 0.7 ft in the upper drift aquifer (model layer 1) to 1.3 ft in the lower drift and Platteville aquifers (model layers 5 and 6, respectively) (table 7). Calculated hydraulic heads in the St. Peter aquifer (model layer 7) were as much as 6.0 ft lower, with the mean decrease for the aquifer being 3.4 ft.

As a result of simulating a hypothetical extension of the Glenwood Shale confining unit in columns 46 to 72, the net boundary flow for the Platteville aquifer (model layer 6) decreased by about 49 percent (table 8). Boundary outflow from the Platteville aquifer increased by 43 percent due to a large reduction (about 98 percent) in the amount of water leaking to the underlying St. Peter aquifer (model layer 7). The water impeded from leaking downward from the drift and Platteville aquifer system (model layers 1-6) to the St. Peter aquifer was discharged by boundary outflow, predominantly through the Platteville aquifer. The net boundary flow for the St. Peter aquifer more than doubled (increased by about 104 percent, table 8). Boundary outflow from the St. Peter aquifer was reduced by 59 percent.

Implications For Migration Of Coal-Tar Derivatives

Based on historical data gathered prior to 1989, the MPCA inferred an area of contamination in the drift and Platteville aquifer system, including the southern portion of the plant site and areas to the south and east (fig. 17). The axis of the contamination plume is coincident with the direction of ground-water movement (east and southeast) in the drift and Platteville aquifer system near the plant site. Dissolved contaminants are carried with the ground water, but generally at a much lower velocity (Freeze and Cherry, 1979). Within the drift and Platteville aquifer system, the velocity of contaminants (polynuclear aromatic hydrocarbons (PAH) and phenolics) is estimated to be at least 20 to 25 times slower than the velocity of the ground water (Environmental Research and Technology, 1983).

FIGURE 17.--NEAR HERE.

Figure 17.--Map showing inferred area of contamination in drift and Platteville aquifer system reported by the Minnesota Pollution Control Agency

Inorganic constituents in ground water in the drift and Platteville aquifer system were selected as tracers by Hult (1984) to evaluate transport processes because concentrations of organic contaminants in the aquifer system were very small. Data presented by Hult (1984) showed that the concentrations of several inorganic constituents near a bedrock valley southeast of the plant site were greater than those in ambient ground water. The distribution and concentration of inorganic constituents including sodium, nitrogen species (ammonia, nitrite, and nitrate), sulfur (sulfide and sulfate), dissolved oxygen, manganese, and iron suggest the main body of the organic-contaminant plume is affected by downward movement of water into the St. Peter aquifer in the vicinity of bedrock valleys. The concentrations of several inorganic constituents from the plant site decreased downgradient in the drift aquifers.

Decreased concentrations of contaminants downgradient, however, does not necessarily reflect retardation or sorption of solute. Contaminants may undergo chemical reactions, physical transformations, or be diluted by mixing (dispersion). Dispersion occurs because of mechanical mixing during fluid advection and because of molecular diffusion due to the thermal-kinetic energy of the solute particles (Freeze and Cherry, 1979).

An undissolved liquid mixture of many individual coal-tar compounds, referred to as a hydrocarbon fluid phase, is in the drift beneath and near the plant site. In the saturated zone, this hydrocarbon fluid phase has moved vertically downward relative to the direction of ground-water flow because it is denser than water. The vertical movement of water and contaminants, both hydrocarbon fluid phase and dissolved contaminants, through the drift and Platteville aquifer system is influenced by the hydraulic properties, sorption characteristics, and presence or absence of confining units.

The study and cross-section model simulations have resulted in increased knowledge of (1) the extent and hydraulic properties of the hydrogeologic units comprising the drift and Platteville aquifer system, particularly the confining units; and (2) local ground-water flow through the aquifer system. The cross-section model results indicate that reasonable estimates of vertical hydraulic conductivities for the drift confining units, a hydraulic property spanning orders of magnitude and involving much uncertainty as to correct values, were obtained. The cross-section model simulations indicate that by increasing the vertical hydraulic conductivity of a confining unit greater downward movement of water from overlying to underlying aquifers would result. Increasing the vertical hydraulic conductivity of confining units in the drift and Platteville aquifer system (model layers 1-6) by a factor of 10 resulted in increases in net flux across the lower boundaries of adjacent aquifers ranging from about 2 percent for the middle drift aquifer (model layer 3) to about 24 percent for the Platteville aquifer (model layer 6). The increased vertical movement of ground water would presumably result in increased vertical movement of contaminants.

The model simulations indicate that most of the vertical movement of water downward through the drift and Platteville aquifer system occurs southeast of the plant site near the bedrock valley. Ground-water flow vertically downward from the unconfined aquifer underlying the plant site is greatly impeded by the upper drift confining unit. The model simulated that about 56 percent of the leakage of water through the upper drift confining unit occurred in model columns 46 to 80. About 48 percent of the downward leakage of water through the lower drift confining unit also occurred in the eastern part of the cross-section (columns 46 to 91). This is because the till and clay comprising the confining unit in this area is sandier and has a greater vertical hydraulic conductivity than in the western part. Of the water that leaks downward through the lower drift confining unit in the western part of the cross-section (columns 1 to 45), about 93 percent occurs in columns 17 to 21 because of thinning of the confining unit and increased sand content. The model simulations indicate that the potential for the vertical movement of contaminants through the drift and Platteville aquifer system is greater southeast of the plant site than directly beneath the plant site, which is the source area of the contaminants.

The bedrock valleys, which were formed by erosion and subsequently filled with permeable glacial drift, have the potential for increasing vertical movement of ground water between the drift and Platteville aquifer system and the St. Peter aquifer.

The cross-section model simulations done for this study indicate the presence or absence of the Glenwood Shale confining unit affects the downward movement of water from the drift and Platteville aquifer system to the underlying St. Peter aquifer. About 99 percent of the leakage to the St. Peter aquifer (model layer 7) along the cross-section model occurs in areas where this confining unit is absent. The results of the model simulations, when combined with data presented by Hult (1984), indicate that increased vertical ground-water flow from the drift and Platteville aquifer system to underlying bedrock aquifers through bedrock valleys results in elevated concentrations and greater vertical movement of contaminants near the valley. Bedrock valleys, therefore, could be major pathways for the vertical movement of contaminants through the drift and Platteville aquifer system to the underlying bedrock aquifers.

The results of the model sensitivity analysis and the simulations of hypothetical variations of the extent of the confining units indicate that the calculated steady-state hydraulic heads are relatively insensitive to large changes in the hydraulic properties and the extent and continuity of confining units. Simulated ground-water flow, however, was significantly affected by these changes, especially by varying the areal extent of the Glenwood Shale confining unit. Additional test drilling to locate discontinuities in confining units might be necessary to ascertain the potential for the vertical movement of contaminants through the drift and Platteville aquifer system. The cross-section model results indicate that field measurements of hydraulic head might not help locate discontinuities in confining units in this hydrogeologic setting.

The cross-section model results are limited in terms of describing the hydrogeology at the plant site. The model represents a two-dimensional section of the drift and Platteville aquifer system along the principal direction of flow in the aquifers. The model cannot represent converging or diverging flow that would be expected near a bedrock valley, or any flow tangent to the alignment of the flow tube. However, the modeling approach used is a valid method of conceptualizing vertical flow through the drift and Platteville aquifer system. The cross-section model integrates many interrelated factors of hydrogeology and the relative effects of discontinuities in confining units on ground-water flow and, presumably, contaminant migration.

SUMMARY AND CONCLUSIONS

The drift and Platteville aquifer system is composed of glacial drift and the underlying Platteville aquifer. Three aquifer units and two confining units have been defined within the drift underlying the area near the site of a former coal-tar distillation and wood-preserving plant in St. Louis Park, Minnesota. The aquifer units, in descending order, are the upper drift, middle drift, and lower drift aquifers. The confining units, in descending order are the upper drift and lower drift confining units.

The upper drift aquifer ranges in composition from peat to sand and gravel, with a maximum saturated thickness of 25 ft. The hydraulic conductivity of the aquifer ranges from about 1 to 25 ft/d in the peat areas and from about 50 to 400 ft/d in the sand and gravel areas. The saturated thickness of the middle drift aquifer ranges from about 5 to 80 ft, but generally is 20 to 30 ft in areas where the aquifer is both overlaid and underlain by a confining unit. The composition of the aquifer varies from silty sand to medium-to-coarse sand and fine gravel, with a range in hydraulic conductivity from about 50 to 500 ft/d. The lower drift aquifer consists of discontinuous sand and gravel deposits overlying Platteville Limestone bedrock and has a maximum saturated thickness of about 20 ft. The aquifer generally is present in a northwest-to-southeast trending band (about 0.3 to 1.0 miles wide) transecting the former plant site and generally is absent outside this band.

The upper drift confining unit is a discontinuous bed of lake deposits, silty to sandy clay, and till underlying the upper drift aquifer. The upper drift confining unit generally is less than 20-ft thick, but may be as much as 62-ft thick. The lower drift confining unit underlies the middle drift aquifer and consists of sandy to silty clay and till ranging in thickness from 0 to 50 ft. Reported vertical hydraulic conductivities for clays and tills with varying amounts of sand range from 0.00004 to 0.2 ft/d.

The drift in the study area is underlain by two subcropping bedrock aquifers, the Platteville and the St. Peter. The Platteville aquifer and underlying Glenwood Shale confining unit are dissected by bedrock valleys in the central and southeastern parts of the study area. The valleys are filled with drift. The thickness of the Platteville aquifer ranges from0 to about 30 ft, with a reported transmissivity of about 9,000 ft^2/d. The Glenwood Shale confining unit ranges from 0 to about 15 ft in thickness and has a vertical hydraulic conductivity estimated to be about 10^{-10} ft/s.

Water in the drift and Platteville aquifer system in the study area generally flows from the west to east under a hydraulic gradient of about 10 ft/mi. Southeast of the plant site water in the drift and Platteville aquifer system generally flows from the northwest to the southeast. Sources of recharge to the drift and Platteville aquifer system are infiltration of precipitation at the land surface, and ground-water inflow to the drift and Platteville aquifers from the west. Discharge from the drift and Platteville aquifer system is by ground-water outflow from the drift and Platteville aquifers to the east, ground-water discharge to surface-water bodies, ground-water evapotranspiration, and ground-water withdrawals by wells. Water also discharges from the drift and Platteville aquifer system by the downward leakage of water to the underlying St. Peter aquifer.

Ground-water flow predominantly is horizontal in aquifers and predominantly vertical in confining units. The confining units control the vertical movement of water through the drift and Platteville aquifer system. Water leaks downward from (1) the unconfined drift aquifer to the middle drift aquifer through the upper drift confining unit, (2) the middle drift aquifer to the lower drift aquifer, where present, or the Platteville aquifer through the lower drift confining unit, and (3) the Platteville aquifer to the St. Peter aquifer through the Glenwood Shale confining unit, where present. The amount of leakage depends on the vertical hydraulic conductivity, the thickness of the confining unit, and the difference in hydraulic heads between the adjacent aquifers. Discontinuities in the confining units greatly affect patterns of flow in the drift and Platteville aquifer system because the vertical hydraulic conductivity of the material filling the discontinuity generally is much greater than that of the confining unit.

A numerical cross-section ground-water-flow computer model was constructed and calibrated for steady-state conditions. The cross-section model was used to test hydrologic concepts of flow through the drift and Platteville aquifer system in the study area, particularly the influence of confining units and bedrock valleys on vertical flow. The model contains eight layers that represent, in descending order: (1) the upper drift aquifer, (2) the upper drift confining unit, (3) the middle drift aquifer, (4) the lower drift confining unit, (5) the lower drift aquifer, (6) the Platteville aquifer, (7) the St. Peter aquifer, and (8) the Prairie du Chien-Jordan aquifer. The Glenwood Shale confining unit and basal St. Peter confining unit are represented in the model by leakage terms that incorporate the thickness and vertical hydraulic conductivity of the unit in each model cell. The simulated recharge to the drift and Platteville aquifer system by precipitation represents the net difference between precipitation and evapotranspiration losses occurring both in the unsaturated zone and at the water table. Measured hydraulic heads in the drift and Platteville aquifer system during December 1987, were used to define boundary conditions and calibrate the model.

The model was calibrated by varying the values of horizontal and vertical hydraulic conductivities of the hydrogeologic units and recharge to the drift and Platteville aquifer system until calculated hydraulic heads acceptably matched measured water levels in wells along the cross-section. The best-fit calculated hydraulic heads in the drift and Platteville aquifer system generally were within 0.2 ft of measured water levels in wells along the cross-section. The mean difference between calculated and measured hydraulic heads, calculated as the sum of the absolute values of the differences divided by the number of wells, was 0.18 ft. The best-fit calibrated value for recharge to the drift and Platteville aquifer system was 6.0 in/yr.

A model-sensitivity analysis, wherein a single hydrologic property was varied while all other properties were held constant, was done to identify the relative effect of adjustments of hydrologic properties on calculated hydraulic heads. The sensitivity analysis indicated that calculated hydraulic heads in the drift and Platteville aquifer system were most sensitive to variations in (1) the horizontal hydraulic conductivities of the middle drift aquifer, (2) the transmissivities of the Platteville and St. Peter aquifers, (3) the vertical hydraulic conductivities of the lower drift confining unit, (4) the vertical hydraulic conductivity of the drift material filling the bedrock valley where the Platteville aquifer and Glenwood Shale confining unit are absent, (5) the vertical hydraulic conductivity of the basal St. Peter confining unit, and (6) recharge. The calculated steady-state hydraulic heads, in general, were relatively insensitive to large changes in the hydraulic properties of the hydrogeologic units, whereas ground-water flow in the drift and Platteville aquifer system was significantly affected.

The water budget calculated using the cross-section model shows that recharge to the uppermost model layers from the infiltration of precipitation accounts for about 41 percent of the total sources of water and boundary inflow from the west accounts for about 59 percent. Boundary inflow to the middle drift aquifer accounts for nearly 32 percent of the total sources of water. The only discharges are boundary outflows from the eastern end of the cross-section model. About 70 percent of the boundary outflow discharges from the Platteville and St. Peter aquifers. Of the remaining 30 percent, about 21 percent discharges from the middle drift aquifer and about 9 percent discharges from the Prairie du Chien-Jordan aquifer.

The water entering the drift and Platteville aquifer system (excluding the underlying St. Peter and Prairie du Chien-Jordan aquifers) discharges from the system by (1) leakage to the underlying St. Peter aquifer (about40 percent), (2) boundary outflow from the Platteville aquifer (about 36 percent), and (3) boundary outflow from the middle drift aquifer (about 24 percent). The presence or absence of the Glenwood Shale confining unit strongly influences the amount and pattern of leakage from the drift and Platteville aquifer system to the underlying St. Peter aquifer. About 99 percent of the total leakage to the St. Peter aquifer flows through the areas where the Glenwood Shale confining unit is absent or discontinuous.

A particle-tracking post-processing program was used to compute ground-water-flow path lines based on output from the cross-section model. Plots of the computed path lines indicate that (1) most of the recharge to the drift and Platteville aquifer system at the land surface moves horizontally in the western part of the cross-section and discharges from the drift and Platteville aquifer system by boundary outflow and leakage to the St. Peter aquifer in the eastern part, and (2) much of the water derived from boundary inflow discharges by leakage to the St. Peter aquifer prior to reaching a bedrock valley in the eastern part of the cross-section.

The calibrated steady-state cross-section model was used to investigate the effects on calculated hydraulic heads and simulated ground-water flow in the drift and Platteville aquifer system of hypothetical changes of the hydraulic properties of confining units and the areal extent of the Glenwood Shale confining unit. The hypothetical changes included (1) increasing the vertical hydraulic conductivity of the lower drift confining unit by a factor of 100 in the western part (model columns 1 to 60) of the cross-section, (2) representing the Glenwood Shale confining unit as continuous in the area west of the bedrock valley (model columns 46 to 62), (3) representing the Glenwood Shale confining unit as continuous across the bedrock valley (model columns 63 to 72), and (4) representing the Glenwood Shale confining unit as continuous across the bedrock valley and the area west of the bedrock valley (model columns 46 to 72), or along the entire cross-section. Increasing the vertical hydraulic conductivity of the lower drift confining unit in the western part of the cross-section resulted in: (1) mean changes in calculated hydraulic heads ranging from -0.8 ft in the upper drift aquifer to +0.6 ft in the lower drift aquifer, (2) increased leakage to the St. Peter aquifer (model layer 7) in the western part of the cross-section, and (3) decreased leakage to the St. Peter aquifer through the bedrock valley in the eastern part of the cross-section.

A hypothetical extension of the Glenwood Shale confining unit along the entire cross-section resulted in rises in calculated hydraulic heads in the drift and Platteville aquifer system (model layers 1-6). Mean rises ranged from 0.7 ft in the upper drift aquifer (model layer 1) to 1.3 ft in the lower drift and Platteville aquifers (model layers 5 and 6, respectively). There was a 98-percent reduction in the amount of water leaking from the Platteville aquifer to the underlying St. Peter aquifer (model layer 7). The ground water impeded from leaking downward to the St. Peter aquifer was discharged by boundary outflow, predominantly through the Platteville aquifer.

A contaminant plume in the drift and Platteville aquifer system underlies the southern part of the plant site and areas to the south and east of the plant site. Dissolved contaminants are carried with the ground water and therefore travel in the same direction, but generally at a much lower velocity. Also, the hydrocarbon-fluid phase has moved vertically downward relative to the direction of ground-water flow in the saturated zone beneath and near the plant site. The model simulations indicate that the potential for the vertical movement of contaminants through the drift and Platteville aquifer system is greater southeast of the plant site near a bedrock valley than it is underlying the plant site.

Bedrock valleys were formed by erosion and subsequently filled with permeable glacial drift. Because the bedrock valleys have the potential for increasing vertical movement of ground water between the drift and Platteville aquifer system and the St. Peter aquifer, they can facilitate the vertical movement of contaminants between the aquifers. Increased vertical ground-water flow from the drift and Platteville aquifer system through the bedrock valleys to underlying bedrock aquifers could result in both elevated concentrations and greater vertical movement of contaminants near the valleys.

Additional test drilling to locate discontinuities in confining units might be necessary to ascertain the potential for the vertical movement of contaminants through the drift and Platteville aquifer system. Results of the cross-section model simulations indicate that field measurements of hydraulic head might not help locate discontinuities in confining units in the hydrogeologic setting near the plant site.

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SUPPLEMENTAL INFORMATION SECTION

LEAKAGE OF WATER BETWEEN MODEL LAYERS AND CALCULATION OF VERTICAL LEAKANCE TERMS

Leakage of water between model layers is dependent on the thicknesses and vertical hydraulic conductivities of adjacent layers and the hydraulic head difference between adjacent layers. Vertical conductance terms are calculated within the model using data from an input array which incorporates both thickness and vertical hydraulic conductivity into a single term, and using horizontal areas calculated from cell dimensions. The input array contains values of vertical hydraulic conductivity divided by thickness, termed the vertical leakance, for each cell in a model layer. Each value of vertical leakance is for the interval between a layer and the layer below it; therefore, vertical leakance is not specified for the lowermost layer in the model. The expression for vertical leakance for the case in which two adjacent model layers are used to represent two vertically adjacent hydrogeologic units is:

$$Vcont_{i,j,k+\frac{1}{2}} = \frac{1}{\dfrac{\left(\dfrac{\Delta v_k}{2}\right)}{K_{Zi,j,k}} + \dfrac{\left(\dfrac{\Delta v_{k+1}}{2}\right)}{K_{Zi,j,k+1}}}$$

where $Vcont_{i,j,k+1/2}$ is the vertical leakance term for leakage between model layers k and k+1;

Δv_k is the thickness of model layer k;

Δv_{k+1} is the thickness of model layer k+1;

$K_{Zi,j,k}$ is the vertical hydraulic conductivity of the upper layer in cell i,j, k; and

$K_{Zi,j,k+1}$ is the vertical hydraulic conductivity of the lower layer in cell i,j,k+1.

The above relation was used to calculate vertical leakance terms for each layer and cell in the model, except for the St. Peter aquifer model layer, and the lowermost layer, the Prairie du Chien-Jordan aquifer.

The thicknesses of each model layer (hydrogeologic unit) by model cell are given below in feet:

Model Layer 1 (Upper drift aquifer)

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12	Column 13	Column 14	Column 15	Column 16	Column 17	Column 18	Column 19	Column 20
37	31	31	27	23	24	21	19	23	22	22	27	27	26	31	31	25	20	20	15

Column 21	Column 22	Column 23	Column 24	Column 25	Column 26	Column 27	Column 28	Column 29	Column 30	Column 31	Column 32	Column 33	Column 34	Column 35	Column 36	Column 37	Column 38	Column 39	Column 40
15	15	15	15	15	15	16	16	16	16	16	16	17	17	17	18	19	19	20	20

Column 41	Column 42	Column 43	Column 44	Column 45	Column 46	Column 47	Column 48	Column 49	Column 50	Column 51	Column 52	Column 53	Column 54	Column 55	Column 56	Column 57	Column 58	Column 59	Column 60
26	27	28	29	31	33	34	35	36	37	38	40	41	42	39	41	43	45	45	45

Model layer 2 (Upper drift confining unit)

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12	Column 13	Column 14	Column 15	Column 16	Column 17	Column 18	Column 19	Column 20
18	10	7	7	7	5	5	5	5	2	2	1	1	2	1	1	2	2	1	2

Column 21	Column 22	Column 23	Column 24	Column 25	Column 26	Column 27	Column 28	Column 29	Column 30	Column 31	Column 32	Column 33	Column 34	Column 35	Column 36	Column 37	Column 38	Column 39	Column 40
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2

Column 41	Column 42	Column 43	Column 44	Column 45	Column 46	Column 47	Column 48	Column 49	Column 50	Column 51	Column 52	Column 53	Column 54	Column 55	Column 56	Column 57	Column 58	Column 59	Column 60
1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2

Column 61	Column 62	Column 63	Column 64	Column 65	Column 66	Column 67	Column 68	Column 69	Column 70	Column 71	Column 72	Column 73	Column 74	Column 75	Column 76	Column 77	Column 78	Column 79	Column 80
2	2	2	2	2	2	2	2	4	5	5	5	5	4	4	4	4	5	5	5

Model layer 3 (Middle drift aquifer)

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12	Column 13	Column 14	Column 15	Column 16	Column 17	Column 18	Column 19	Column 20
15	15	15	15	15	15	15	20	15	15	15	15	15	15	15	15	15	15	15	10

Column 21	Column 22	Column 23	Column 24	Column 25	Column 26	Column 27	Column 28	Column 29	Column 30	Column 31	Column 32	Column 33	Column 34	Column 35	Column 36	Column 37	Column 38	Column 39	Column 40
15	15	15	15	15	15	15	15	20	20	20	20	20	20	20	20	25	25	25	20

Column 41	Column 42	Column 43	Column 44	Column 45	Column 46	Column 47	Column 48	Column 49	Column 50	Column 51	Column 52	Column 53	Column 54	Column 55	Column 56	Column 57	Column 58	Column 59	Column 60
20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20

Column 61	Column 62	Column 63	Column 64	Column 65	Column 66	Column 67	Column 68	Column 69	Column 70	Column 71	Column 72	Column 73	Column 74	Column 75	Column 76	Column 77	Column 78	Column 79	Column 80
20	20	25	25	25	25	25	25	15	15	15	15	15	20	20	20	20	20	20	20

Column 81	Column 82	Column 83	Column 84	Column 85	Column 86	Column 87	Column 88	Column 89	Column 90
25	25	25	25	25	25	25	25	30	25

Model layer 4 (Lower drift confining unit)

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12	Column 13	Column 14	Column 15	Column 16	Column 17	Column 18	Column 19	Column 20
20	20	20	20	20	20	20	10	5	2	2	2	2	2	2	5	10	15	20	25

Column 21	Column 22	Column 23	Column 24	Column 25	Column 26	Column 27	Column 28	Column 29	Column 30	Column 31	Column 32	Column 33	Column 34	Column 35	Column 36	Column 37	Column 38	Column 39	Column 40
25	25	25	25	25	25	20	20	15	15	15	15	15	15	10	10	10	15	15	15

Column 41	Column 42	Column 43	Column 44	Column 45	Column 46	Column 47	Column 48	Column 49	Column 50	Column 51	Column 52	Column 53	Column 54	Column 55	Column 56	Column 57	Column 58	Column 59	Column 60
15	15	15	15	15	15	15	15	15	15	15	25	25	25	25	25	25	25	25	25

Column 61	Column 62	Column 63	Column 64	Column 65	Column 66	Column 67	Column 68	Column 69	Column 70	Column 71	Column 72	Column 73	Column 74	Column 75	Column 76	Column 77	Column 78	Column 79	Column 80
25	25	25	25	25	25	25	25	30	30	30	30	30	30	30	30	30	30	30	30

Column 81	Column 82	Column 83	Column 84	Column 85	Column 86	Column 87	Column 88	Column 89	Column 90
30	30	30	30	30	30	35	35	35	40

Model layer 5 (Lower drive aquifer)

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12	Column 13	Column 14	Column 15	Column 16	Column 17	Column 18	Column 19	Column 20
5	5	5	5	5	5	10	10	15	20	20	20	20	20	20	15	10	10	10	10

Column 21	Column 22	Column 23	Column 24	Column 25	Column 26	Column 27	Column 28	Column 29	Column 30	Column 31	Column 32	Column 33	Column 34	Column 35	Column 36	Column 37	Column 38	Column 39	Column 40
10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	5	5	5

Column 41	Column 42	Column 43	Column 44	Column 45	Column 46	Column 47	Column 48	Column 49	Column 50	Column 51	Column 52	Column 53	Column 54	Column 55	Column 56	Column 57	Column 58	Column 59	Column 60
5	5	5	5	5	10	10	10	10	10	10	10	10	10	10	10	15	20	20	20

Column 61	Column 62	Column 63	Column 64	Column 65	Column 66	Column 67	Column 68	Column 69	Column 70	Column 71	Column 72	Column 73	Column 74	Column 75	Column 76	Column 77	Column 78	Column 79	Column 80
20	20	20	20	20	20	20	20	20	20	20	20	15	15	10	10	10	10	10	10

Column 81	Column 82	Column 83	Column 84	Column 85	Column 86	Column 87	Column 88	Column 89	Column 90
10	10	10	10	10	10	5	5	5	10

Model layer 6 (Platteville aquifer)

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12	Column 13	Column 14	Column 15	Column 16	Column 17	Column 18	Column 19	Column 20
25	25	25	25	25	20	20	20	20	15	15	15	15	15	15	15	15	20	20	15

Column 21	Column 22	Column 23	Column 24	Column 25	Column 26	Column 27	Column 28	Column 29	Column 30	Column 31	Column 32	Column 33	Column 34	Column 35	Column 36	Column 37	Column 38	Column 39	Column 40
15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	14	13	12

Column 41	Column 42	Column 43	Column 44	Column 45	Column 46	Column 47	Column 48	Column 49	Column 50	Column 51	Column 52	Column 53	Column 54	Column 55	Column 56	Column 57	Column 58	Column 59	Column 60
12	11	11	10	9	8	8	7	7	7	6	6	5	5	5	4	3	2	1	1

Column 61	Column 62	Column 63	Column 64	Column 65	Column 66	Column 67	Column 68	Column 69	Column 70	Column 71	Column 72	Column 73	Column 74	Column 75	Column 76	Column 77	Column 78	Column 79	Column 80
1	1	1	1	1	1	1	1	1	1	1	1	10	10	15	20	20	20	20	20

Column 81	Column 82	Column 83	Column 84	Column 85	Column 86	Column 87	Column 88	Column 89	Column 90
20	20	20	20	20	20	20	20	20	20

The values for vertical hydraulic conductivities from the calibrated best-fit simulation for each model layer (hydrogeologic unit) by model cell are given below in feet per day:

Model layer 1 (Upper drift aquifer)

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12	Column 13	Column 14	Column 15	Column 16
30	30	30	30	30	30	30	10	5.0	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Column 17	Column 18	Column 19	Column 20	Column 21	Column 22	Column 23	Column 24	Column 25	Column 26	Column 27	Column 28	Column 29	Column 30	Column 31	Column 32
.01	.01	.01	.01	.01	.01	15	15	15	15	15	15	15	15	15	15

Column 33	Column 34	Column 35	Column 36	Column 37	Column 38	Column 39	Column 40	Column 41	Column 42	Column 43	Column 44	Column 45	Column 46	Column 47	Column 48
15	15	15	15	15	15	15	15	20	20	20	20	20	20	20	20

Column 49	Column 50	Column 51	Column 52	Column 53	Column 54	Column 55	Column 56	Column 57	Column 58	Column 59	Column 60
20	20	20	20	20	20	20	30	30	30	30	30

Model layer 2 (Upper drift confining unit)

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12	Column 13	Column 14	Column 15	Column 16
0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.04	0.04	0.04	0.04

Column 17	Column 18	Column 19	Column 20	Column 21	Column 22	Column 23	Column 24	Column 25	Column 26	Column 27	Column 28	Column 29	Column 30	Column 31	Column 32
.04	.04	.01	.01	.01	.01	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02

Column 33	Column 34	Column 35	Column 36	Column 37	Column 38	Column 39	Column 40	Column 41	Column 42	Column 43	Column 44	Column 45	Column 46	Column 47	Column 48
.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02

Column 49	Column 50	Column 51	Column 52	Column 53	Column 54	Column 55	Column 56	Column 57	Column 58	Column 59	Column 60	Column 61	Column 62	Column 63	Column 64
.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02

Column 65	Column 66	Column 67	Column 68	Column 69	Column 70	Column 71	Column 72	Column 73	Column 74	Column 75	Column 76	Column 77	Column 78	Column 79	Column 80
.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02

Model layer 3 (Middle drift aquifer)

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12	Column 13	Column 14	Column 15	Column 16
40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
Column 17	Column 18	Column 19	Column 20	Column 21	Column 22	Column 23	Column 24	Column 25	Column 26	Column 27	Column 28	Column 29	Column 30	Column 31	Column 32
40	40	40	40	50	50	50	50	50	50	50	50	50	50	50	50
Column 33	Column 34	Column 35	Column 36	Column 37	Column 38	Column 39	Column 40	Column 41	Column 42	Column 43	Column 44	Column 45	Column 46	Column 47	Column 48
50	50	50	50	50	50	50	50	5	5	5	5	5	5	5	5
Column 49	Column 50	Column 51	Column 52	Column 53	Column 54	Column 55	Column 56	Column 57	Column 58	Column 59	Column 60	Column 61	Column 62	Column 63	Column 64
5	5	5	5	5	5	5	5	5	5	5	5	10	10	10	10
Column 65	Column 66	Column 67	Column 68	Column 69	Column 70	Column 71	Column 72	Column 73	Column 74	Column 75	Column 76	Column 77	Column 78	Column 79	Column 80
10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Column 81	Column 82	Column 83	Column 84	Column 85	Column 86	Column 87	Column 88	Column 89	Column 90						
15	15	15	15	15	20	20	20	20	20						

Model layer 4 (Lower drift confining unit)

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12	Column 13	Column 14	Column 15	Column 16
0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Column 17	Column 18	Column 19	Column 20	Column 21	Column 22	Column 23	Column 24	Column 25	Column 26	Column 27	Column 28	Column 29	Column 30	Column 31	Column 32
.002	.004	.004	.004	.004	.0002	.0002	.0002	.0002	.0002	.0002	.0002	.0002	.0002	.0002	.0002

Column 33	Column 34	Column 35	Column 36	Column 37	Column 38	Column 39	Column 40	Column 41	Column 42	Column 43	Column 44	Column 45	Column 46	Column 47	Column 48
.0002	.0002	.0002	.0002	.0004	.0004	.0004	.0004	.0004	.0004	.0004	.0004	.0004	.0004	.0004	.0004

Column 49	Column 50	Column 51	Column 52	Column 53	Column 54	Column 55	Column 56	Column 57	Column 58	Column 59	Column 60	Column 61	Column 62	Column 63	Column 64
.0004	.0004	.0004	.01	.01	.01	.01	.01	.01	.01	.01	.01	.2	.2	.2	.2

Column 65	Column 66	Column 67	Column 68	Column 69	Column 70	Column 71	Column 72	Column 73	Column 74	Column 75	Column 76	Column 77	Column 78	Column 79	Column 80
.2	.2	.2	.2	.18	.18	.18	.18	.18	.18	.18	.18	.18	.18	.18	.18

Column 81	Column 82	Column 83	Column 84	Column 85	Column 86	Column 87	Column 88	Column 89	Column 90
.02	.02	.02	.02	.02	.02	.02	.02	.02	.02

Model layer 5 (Lower drift aquifer)

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12	Column 13	Column 14	Column 15	Column 16
0.02	0.02	0.02	0.02	0.02	10	20	20	20	20	20	20	20	20	20	20

Column 17	Column 18	Column 19	Column 20	Column 21	Column 22	Column 23	Column 24	Column 25	Column 26	Column 27	Column 28	Column 29	Column 30	Column 31	Column 32
.02	.02	.02	40	40	40	40	40	40	40	40	40	40	40	40	40

Column 33	Column 34	Column 35	Column 36	Column 37	Column 38	Column 39	Column 40	Column 41	Column 42	Column 43	Column 44	Column 45	Column 46	Column 47	Column 48
40	50	50	10	10	10	10	10	10	10	10	10	10	30	30	30

Column 49	Column 50	Column 51	Column 52	Column 53	Column 54	Column 55	Column 56	Column 57	Column 58	Column 59	Column 60	Column 61	Column 62	Column 63	Column 64
30	30	30	30	30	30	30	30	30	30	30	30	10	10	.04	.04

Column 65	Column 66	Column 67	Column 68	Column 69	Column 70	Column 71	Column 72	Column 73	Column 74	Column 75	Column 76	Column 77	Column 78	Column 79	Column 80
.04	.04	.04	.04	.04	.04	.04	.04	10	10	5	5	5	5	5	5

Column 81	Column 82	Column 83	Column 84	Column 85	Column 86	Column 87	Column 88	Column 89	Column 90
5	5	5	5	5	5	5	5	5	5

Model layer 6 (Platteville aquifer)

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12	Column 13	Column 14	Column 15	Column 16
2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75

Column 17	Column 18	Column 19	Column 20	Column 21	Column 22	Column 23	Column 24	Column 25	Column 26	Column 27	Column 28	Column 29	Column 30	Column 31	Column 32
2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75

Column 33	Column 34	Column 35	Column 36	Column 37	Column 38	Column 39	Column 40	Column 41	Column 42	Column 43	Column 44	Column 45	Column 46	Column 47	Column 48
2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75

Column 49	Column 50	Column 51	Column 52	Column 53	Column 54	Column 55	Column 56	Column 57	Column 58	Column 59	Column 60	Column 61	Column 62	Column 63	Column 64
2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	.04	.04

Column 65	Column 66	Column 67	Column 68	Column 69	Column 70	Column 71	Column 72	Column 73	Column 74	Column 75	Column 76	Column 77	Column 78	Column 79	Column 80
.04	.04	.04	.40	.04	.04	.04	.04	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75

Column 81	Column 82	Column 83	Column 84	Column 85	Column 86	Column 87	Column 88	Column 89	Column 90
2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75

The Glenwood Shale confining unit, which underlies the Platteville aquifer and the basal St. Peter confining unit, which underlies the St. Peter aquifer are not represented as layers in the model. Ground-water flow in these confining units is predominantly vertical, with no significant horizontal component of flow. The assumption is made that these confining units make no measurable contribution to the horizontal conductance of the overlying and underlying layers. In each case, the confining unit is treated simply as the vertical conductance between the overlying and underlying aquifers. This formulation for the treatment of confining units is frequently referred to as the "quasi-three-dimensional" approach (McDonald and Harbaugh, 1988). The expression for vertical leakance in this case, in which a confining unit separates two aquifers and is not represented as a layer in the model, reduces to:

$$Vcont_{i,j,k+1/2}=Kzc/\Delta zc$$

where $Vcont_{i,j,k+1/2}$ is the vertical leakance term for leakage between model layers k and k+1 (aquifers overlying and underlying the confining unit);

K_{zc} is the vertical hydraulic conductivity of the confining unit; and

Δz_c is the thickness of the confining unit,

assuming that the vertical hydraulic conductivity of the confining unit is much smaller than the vertical hydraulic conductivities of the aquifers. The above relation was used to calculate vertical leakance terms for model layers 6 and 7, representing the Platteville and St. Peter aquifers, respectively.

MODEL INPUT DATA USED FOR CALIBRATED STEADY-STATE CROSS-SECTION MODEL

Listings 1 to 5 contain values for a particular modular-model package as defined by McDonald and Harbaugh (1988). Listing 6 contains values for the main data file required to compute path lines as defined by Pollock (1989).

Listing 1. Input values for the BASIC package of the MODULAR program.

2. Input values for the BCF package of the MODULAR program.

3. Input values for the RECHARGE package of the MODULAR program.

4. Input values for SSOR package of the MODULAR program.

5. Input values for the Output Control Option of the BASIC package of the MODULAR program.

6. Input values for the main data file of the particle-tracking post-processing program.

Listing 1. Input values for the BASIC package of the MODULAR program

ST. LOUIS PARK CROSS-SECTION MODEL STEADY STATE 8-LAYERS

```
          8         1        91          1         1
07 00 00 00 00 00 00 09 00 00 10 13
          0         1
          5         1              (20I4)        -1          BOUNDARY ARRAY 1
 -1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
  0   0   0   0   0   0   0   0   0   0   0

          5         1              (20I4)        -1          BOUNDARY ARRAY 2
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  0   0   0   0   0   0   0   0   0   0   0

          5         1              (20I4)        -1          BOUNDARY ARRAY 3
 -1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1  -1

          5         1              (20I4)        -1          BOUNDARY ARRAY 4
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1

          5         1              (20I4)        -1          BOUNDARY ARRAY 5
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1

          5         1              (20I4)        -1          BOUNDARY ARRAY 6
 -1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1  -1

          5         1              (20I4)        -1          BOUNDARY ARRAY 7
 -1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1  -1

          5         1              (20I4)        -1          BOUNDARY ARRAY 8
 -1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
  1   1   1   1   1   1   1   1   1   1  -1
```

Listing 1. Input values for the BASIC package of the MODULAR program--Continued

```
999999999.
         5        1.0             (16F5.1)        -1          START HEAD 1
890.0890.0980.0890.0890.0890.0890.0890.0890.0890.0890.0890.0890.0890.0890.0890.0
890.0890.0890.0890.0890.0890.0890.0890.0890.0890.0890.0891.0891.0891.0891.0891.0
892.0892.0893.0894.0894.0895.0895.0895.0896.0897.0898.0900.0900.0900.0900.0900.0
900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0
900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0
900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0900.0

         5        1.0             (16F5.1)        -1          START HEAD 2
888.8888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0
888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0
885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0
880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0
875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0
872.5872.5872.5872.5872.5872.5872.5872.5872.5872.5870.9

         5        1.0             (16F5.1)        -1          START HEAD 3
888.8888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0
888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0888.0
885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0
880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0
875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0
872.5872.5872.5872.5872.5872.5872.5872.5872.5872.5870.9

         5        1.0             (16F5.1)        -1          START HEAD 4
885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0
885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0
885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0
880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0
875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0
872.5872.5872.5872.5872.5872.5872.5872.5872.5872.5868.6

         5        1.0             (16F5.1)        -1          START HEAD 5
884.9884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5
884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5
884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5884.5
880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0
875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0
873.0873.0873.0873.0873.0873.0873.0873.0873.0873.0872.7

         5        1.0             (16F5.1)        -1          START HEAD 6
885.2885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0
885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0
885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0885.0
880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0880.0
875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0
872.5872.5872.5872.5872.5872.5872.5872.5872.5872.5868.6

         5        1.0             (16F5.1)        -1          START HEAD 7
878.0877.0877.0877.0877.0877.0877.0877.0877.0877.0877.0877.0877.0877.0877.0877.0
875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0
875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0
875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0875.0
870.0870.0870.0870.0870.0870.0870.0870.0870.0870.0870.0870.0870.0870.0870.0870.0
870.0870.0870.0870.0870.0870.0870.0870.0870.0870.0864.0
         5        1.0             (16F5.1)        -1          START HEAD 8
805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0
805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0
805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0
805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0805.0
804.0804.0804.0804.0804.0804.0804.0804.0804.0804.0804.0804.0804.0804.0804.0804.0
803.0803.0803.0803.0803.0803.0803.0803.0803.0803.0803.0
31536000.         1       1.0
```

Listing 2. Input values for the BCF package of the MODULAR program

```
          1         53
 1 3 3 0 0 0 0 0
          7        1.0                (8F5.1)           0    ANISOTROPY FACTORS
  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0
          0       100.                                           DELR
          0       100.                                           DELC
          71.1574E-05                 (20F4.0)          -1       COND1  FAC   1   FT/DAY
 300 300 300 300 300 300 300 100  50   2   2   2   2   2   2   2   2   2   2   2
   2   5 150 150 150 150 150 150 150 150 150 150 150 150 150 150 150 150 150 150
 200 200 200 200 200 200 200 200 200 200 200 200 200 200 200 300 300 300 300 300
 400 400 400 400 400 400 400 400 400 400 400 400 400 400 400 400 400 400 400 400
 400 400 400 400 400 400 400  10  10  10  10

          7        1.0                (20F4.0)          -1             BOTTOM ELEV
 885 885 880 880 880 875 875 875 870 870 870 865 865 865 860 860 865 870 870 875
 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875
 870 870 870 870 870 870 870 870 870 870 870 870 870 870 875 875 875 875 875 875
 875 875 880 880 880 880 880 880 885 890 890 890 890 890 890 890 890 895 895 895
 895 895 895 895 895 895 895 895 895 895 895

          7        1.0                (5G16.4)          -1      VCONT LAYERS12
       0.2569D-07       0.4620D-07       0.7690D-07       0.7694D-07       0.7697D-07
       0.1153D-06       0.1154D-06       0.1147D-06       0.1132D-06       0.1006D-07
       0.1006D-07       0.8903D-08       0.8903D-08       0.8735D-08       0.7716D-08
       0.7716D-08       0.9448D-08       0.1129D-07       0.1157D-07       0.1447D-07
       0.1653D-07       0.1653D-07       0.2480D-04       0.2480D-04       0.2480D-04
       0.2480D-04       0.2170D-04       0.2170D-04       0.2170D-04       0.2170D-04
       0.2170D-04       0.2170D-04       0.2170D-04       0.2170D-04       0.2170D-04
       0.1929D-04       0.1929D-04       0.1929D-04       0.1736D-04       0.2284D-06
       0.1781D-04       0.1781D-04       0.1653D-04       0.1653D-04       0.1543D-04
       0.1447D-04       0.1362D-04       0.1362D-04       0.1286D-04       0.1286D-04
       0.1218D-04       0.1157D-04       0.1157D-04       0.1102D-04       0.2272D-06
       0.2284D-06       0.2283D-06       0.2281D-06       0.2281D-06       0.2281D-06
       0.2290D-06       0.2290D-06       0.2292D-06       0.2292D-06       0.2293D-06
       0.2294D-06       0.2295D-06       0.2295D-06       0.1153D-06       0.1153D-06
       0.1153D-06       0.1154D-06       0.1154D-06       0.1154D-06       0.1155D-06
       0.1155D-06       0.1155D-06       0.1155D-06       0.1155D-06       0.1155D-06
       0.1155D-06       0.4209D-04       0.4209D-04       0.5144D-04       0.5144D-04
       0.5144D-04       0.5144D-04       0.2314D-07       0.2314D-07       0.2314D-07
       0.2314D-07
          71.1574E-05                 (20F4.0)          -1             COND2  FAC   1 FT/DAY
 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 30. 30. 30. 30. 30. 30. 30. 10. 10.
 10. 10. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20.
 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20.
 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20. 20.
 20.200.200.200.200.200.200.200.200.200.200.

          7        1.0                (20F4.0)          -1             AQ. BOTTOM
865.865.865.865.865.865.865.865.860.860.860.860.860.855.855.855.855.860.865.865.
870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.865.
865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.
865.865.870.870.870.870.870.870.865.865.865.865.865.870.870.870.870.870.870.870.
875.875.875.875.875.875.875.875.880.880.880.
```

Listing 2. Input values for the BCF package of the MODULAR program--Continued

```
       7         1.0               (5G16.4)           -1     VCONT LAYERS23
  0.2571D-07       0.4626D-07       0.7707D-07       0.7707D-07       0.7707D-07
  0.1155D-06       0.1155D-06       0.1155D-06       0.1155D-06       0.2307D-06
  0.2307D-06       0.6614D-04       0.6614D-04       0.4597D-06       0.6614D-04
  0.6614D-04       0.4597D-06       0.4597D-06       0.6614D-04       0.1156D-06
  0.8267D-04       0.8267D-04       0.8267D-04       0.8267D-04       0.8267D-04
  0.8267D-04       0.8267D-04       0.8267D-04       0.5787D-04       0.5787D-04
  0.5787D-04       0.5787D-04       0.5787D-04       0.5787D-04       0.5787D-04
  0.5787D-04       0.4823D-04       0.4823D-04       0.4823D-04       0.2306D-06
  0.5787D-05       0.5787D-05       0.5787D-05       0.5787D-05       0.5787D-05
  0.5787D-05       0.5787D-05       0.5787D-05       0.5787D-05       0.5787D-05
  0.5787D-05       0.5787D-05       0.5787D-05       0.5787D-05       0.2226D-06
  0.2226D-06       0.2226D-06       0.2226D-06       0.2226D-06       0.2226D-06
  0.2269D-06       0.2269D-06       0.2261D-06       0.2261D-06       0.2261D-06
  0.2261D-06       0.2261D-06       0.2261D-06       0.1149D-06       0.1149D-06
  0.1149D-06       0.1149D-06       0.1149D-06       0.1146D-06       0.1146D-06
  0.1146D-06       0.1146D-06       0.1146D-06       0.1146D-06       0.1146D-06
  0.1148D-06       0.1286D-04       0.1286D-04       0.1286D-04       0.1286D-04
  0.1653D-04       0.1653D-04       0.1653D-04       0.1362D-04       0.1653D-04
  0.1653D-04

       7         1.0               (20F4.0)           -1          AQ. TOP
885.885.880.880.880.875.875.875.870.870.870.865.865.865.860.860.865.870.870.875.
875.875.875.875.875.875.875.875.875.875.875.875.875.875.875.875.875.875.875.875.
870.870.870.870.870.870.870.870.870.870.870.870.870.870.875.875.875.875.875.875.
875.875.880.880.880.880.880.880.885.890.890.890.890.890.890.890.890.895.895.895.
895.895.895.900.900.900.900.900.900.900.900.

       71.1574E-03                 (20F4.1)           -1          COND3 FAC  100 FT/DAY
 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0
 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0
 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
 1.5 1.5 1.5 1.5 1.5 2.0 2.0 2.0 2.0 2.0 2.0

       7         1.0               (20F4.0)           -1          AQ. BOTTOM
850.850.850.850.850.850.850.845.845.845.845.845.845.840.840.840.840.845.845.845.
845.845.845.845.845.845.845.845.850.850.850.850.850.850.850.850.845.845.845.845.
845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.
845.845.845.845.845.845.845.845.850.850.850.850.850.850.850.850.850.850.850.850.
850.850.850.850.850.850.850.850.850.855.855.

       7         1.0               (5G16.4)           -1     VCONT LAYERS34
  0.2314D-09       0.2314D-09       0.2314D-09       0.2314D-09       0.2314D-09
  0.2314D-09       0.2314D-09       0.4625D-09       0.1138D-09       0.2237D-09
  0.2237D-09       0.2237D-09       0.2237D-06       0.2237D-06       0.2237D-06
  0.1138D-06       0.0926D-05       0.1323D-05       0.0926D-05       0.0772D-05
  0.0772D-05       0.1929D-09       0.1929D-09       0.1929D-09       0.1929D-09
  0.1929D-09       0.2315D-09       0.2315D-09       0.3307D-09       0.3307D-09
  0.3307D-09       0.3307D-09       0.3307D-09       0.3307D-09       0.4630D-09
  0.4630D-09       0.9259D-09       0.6614D-09       0.6614D-09       0.6614D-09
  0.6613D-09       0.6613D-09       0.6613D-09       0.6613D-09       0.6613D-09
  0.6613D-09       0.6613D-09       0.6613D-09       0.6613D-09       0.6613D-09
  0.6613D-09       0.9629D-09       0.9629D-09       0.9629D-09       0.9629D-09
  0.9629D-08       0.9629D-08       0.9629D-08       0.9629D-08       0.9629D-08
  0.1897D-06       0.1897D-06       0.1891D-06       0.1891D-06       0.1891D-06
  0.1891D-06       0.1891D-06       0.1891D-06       0.1377D-06       0.1377D-06
  0.1377D-06       0.1377D-06       0.1377D-06       0.1372D-06       0.1372D-06
  0.1372D-08       0.1372D-08       0.1372D-08       0.1372D-08       0.1372D-08
  0.1542D-08       0.1542D-08       0.1542D-08       0.1542D-08       0.1542D-08
  0.1542D-08       0.1361D-08       0.1361D-08       0.1360D-08       0.1157D-08
  0.1157D-08
```

Listing 2. Input values for the BCF package of the MODULAR program--Continued

```
         7       1.0              (20F4.0)         -1          AQ. TOP
865.865.865.865.865.865.865.865.860.860.860.860.860.855.855.855.855.860.865.865.
870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.865.
865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.
865.865.870.870.870.870.870.870.865.865.865.865.865.870.870.870.870.870.870.870.
875.875.875.875.875.875.875.875.880.880.880.

         71.1574E-05              (16F5.0)         -1     TRANS4 FAC 1.0 FT2/DAY
 200  200  200  200  200  200  200  100   50   20   20   20   20   20   20   50
 100  150  375  375  375  375  375  375  375  375  400  400  300  300  300  300
 300  300  200  200  300  300  300  300  300  300  300  300  300  300  300  300
 300  300  300  750  750  750  750  750  750  750  750  750  750  750  750  750
 750  750  750  750  900  900  900  900  900  900  900  900  900  900  900  900
 300  300  300  300  300  300  350  350  350  400  400

         7       1.0              (5G16.4)         -1     VCONT LAYERS45
    0.1929D-09       0.1929D-09      0.1929D-09      0.1929D-09      0.1929D-09
    0.2314D-09       0.2314D-09      0.4625D-09      0.1118D-09      0.2104D-09
    0.2104D-09       0.2104D-09      0.2104D-07      0.2104D-07      0.2104D-07
    0.1118D-07       0.0842D-05      0.1157D-05      0.0842D-05      0.0772D-05
    0.0772D-05       0.1929D-09      0.1929D-09      0.1929D-09      0.1929D-09
    0.1929D-09       0.2315D-09      0.2315D-09      0.3307D-09      0.3307D-09
    0.3307D-09       0.3307D-09      0.3307D-09      0.3307D-09      0.4630D-09
    0.4630D-09       0.9259D-09      0.6614D-09      0.6614D-09      0.6614D-09
    0.6614D-09       0.6614D-09      0.6614D-09      0.6614D-09      0.6614D-09
    0.6614D-09       0.6614D-09      0.6614D-09      0.6614D-09      0.6614D-09
    0.6614D-09       0.9644D-08      0.9644D-08      0.9644D-08      0.9644D-08
    0.9644D-08       0.9643D-08      0.9642D-08      0.9642D-08      0.9642D-08
    0.1897D-06       0.1897D-06      0.1867D-06      0.1867D-06      0.1867D-06
    0.1867D-06       0.1867D-06      0.1867D-06      0.1736D-06      0.1736D-06
    0.1736D-06       0.1736D-06      0.1377D-06      0.1377D-06      0.1372D-06
    0.1372D-06       0.1372D-06      0.1372D-06      0.1372D-06      0.1372D-06
    0.1541D-07       0.1541D-07      0.1541D-07      0.1541D-07      0.1541D-07
    0.1541D-07       0.1361D-07      0.1361D-07      0.1361D-07      0.1156D-07
    0.1156D-07

         71.1574E-05              (16F5.0)         -1     TRANS5 FAC 1.0 FT2/DAY
  50   50   50   50   50  500 2000 2000 3000 4000 4000 4000 4000 4000 4000 3000
 100  100  100 4000 4000 4000 4000 4000 4000 4000 4000 4000 4000 4000 4000 4000
4000 5000 5000  100  100  100  100  100  100  100  100  100  100 3000 3000 3000
3000 3000 3000 3000 3000 3000 3000 3000 3000 3000 3000 3000 1125 1125 1125  750
 750  750  750  750  750  750  750  750  750  750  750  750  900  900  900  900
 900  900  900  900  900  900  900  900  900  900  900
```

Listing 2. Input values for the BCF package of the MODULAR program--Continued

```
      7          1.0                (5G16.4)           -1       VCONT LAYERS56
   0.1109D-09        0.1109D-09        0.1109D-09        0.1109D-09        0.1109D-09
   0.3017D-09        0.2978D-09        0.2978D-09        0.2903D-09        0.3800D-09
   0.3800D-06        0.3800D-06        0.3800D-06        0.3800D-06        0.3800D-06
   0.3283D-05        0.4583D-05        0.4563D-05        0.4563D-05        0.4583D-05
   0.4583D-05        0.4334D-06        0.4334D-06        0.4334D-06        0.4334D-06
   0.4334D-06        0.4334D-06        0.4334D-06        0.4334D-06        0.4334D-06
   0.4334D-06        0.4334D-06        0.4334D-06        0.4375D-06        0.4375D-06
   0.3800D-06        0.3800D-06        0.4216D-06        0.4859D-06        0.4859D-06
   0.4859D-06        0.5735D-06        0.5735D-06        0.5735D-06        0.6995D-06
   0.7139D-06        0.7139D-06        0.9203D-06        0.9203D-06        0.9203D-06
   0.9203D-06        0.9203D-06        0.1295D-04        0.1295D-04        0.1295D-04
   0.1295D-04        0.1939D-04        0.1661D-04        0.3472D-04        0.3472D-04
   0.1157D-04        0.1157D-04        0.1157D-06        0.1157D-06        0.1157D-06
   0.1157D-06        0.1157D-06        0.1157D-06        0.1157D-06        0.1157D-06
   0.1157D-06        0.1157D-06        0.4596D-08        0.4596D-08        0.3264D-08
   0.2496D-08        0.2496D-08        0.2496D-08        0.2496D-08        0.2496D-08
   0.2496D-08        0.2496D-08        0.2496D-08        0.2496D-08        0.2496D-08
   0.2496D-08        0.2867D-08        0.2867D-08        0.2867D-08        0.2496D-08
   0.2496D-08

      71.1574E-05                  (16F5.0)            -1       TRANS6 FAC 1.0 FT2/DAY
6875 6875 6875 6875 6875 5500 5500 5500 5500 5500 5500 5500 5500 5500 5500 5500
5500 5500 5500 5500 4125 4125 4125 4125 4125 4125 4125 4125 4125 4125 4125 4125
4125 4125 4125 4125 4125 3850 3575 3300 3300 3025 3025 2750 2475 2200 2200 1925
1925 1925 1650 1650 1500 1500 1500 1500 1500 1500 1500 1500 1500 1500 1500 1500
1500 1500 1500 1500 1500 1500 1500 1500 2600 2750 4125 5500 5500 5500 5500 5500
5500 5500 5500 5500 5500 5500 5500 5500 5500 5500 5500

      7          1.0                (5G16.4)           -1       VCONT LAYERS67
   0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10
   0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10
   0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10
   0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10
   0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10
   0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10
   0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10
   0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10
   0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10
   0.2894D-07        0.2894D-07        0.2894D-07        0.2894D-07        0.2894D-07
   0.2894D-07        0.2894D-07        0.2894D-07        0.2894D-07        0.2894D-07
   0.2894D-07        0.2894D-07        0.2894D-07        0.2894D-07        0.2894D-07
   0.2894D-07        0.2894D-07        0.2300D-07        0.2300D-07        0.2300D-07
   0.2300D-07        0.2300D-07        0.2300D-07        0.2300D-07        0.2300D-07
   0.2300D-07        0.2300D-07        0.2315D-10        0.2315D-10        0.2315D-10
   0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10
   0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10
   0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10        0.2315D-10
   0.2315D-10

      0     .03617                                              TRANS7 25 FT/DAY
      01.1574E-11                                                    VCONT LAYERS78
      0     .12731                                                   TRANS8 55 FT/DAY
```

Listing 3. Input values for the RECHARGE package of the MODULAR program

```
          3         53          1
          1          0
          91.5855E-08            (20F4.1)           6.0 IN/YR
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
```

Listing 4. Input values for the SSOR package of the MODULAR program

```
  75
 1.0        .01         1
```

Listing 5. Input values for the Output Control Option of the BASIC package of the MODULAR program

```
0          0          54          0
0         -1          -1         -1
1          1           1          1
```

Listing 6. Input values for the main data file of the particle-tracking post-processing program

```
        91            1            8            2            0
    9                                      53   54
1 3 3 0 0 0 0 0
0 0 0 0 0 1 1 0
          0        100.                                      0       DELR
          0        100.                                      0       DELC
        15         1.0              (20F4.0)                 1                BOTT L1
885 885 880 880 880 875 875 875 870 870 870 865 865 865 860 860 865 870 870 875
875 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875
870 870 870 870 870 870 870 870 870 870 870 870 870 870 875 875 875 875 875 875
875 875 880 880 880 880 880 880 885 890 890 890 890 890 890 890 890 895 895 895
895 895 895 895 895 895 895 895 895 895 895

        15         1.0              (20F4.0)                 1                TOP L2
885 885 880 880 880 875 875 875 870 870 870 865 865 865 860 860 865 870 870 875
875 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875 875
870 870 870 870 870 870 870 870 870 870 870 870 870 870 875 875 875 875 875 875
875 875 880 880 880 880 880 880 885 890 890 890 890 890 890 890 890 895 895 895
895 895 895 895 895 895 895 895 895 895 895

        15         1.0              (20F4.0)                 1           BOTT L2
865.865.865.865.865.865.865.865.860.860.860.860.860.855.855.855.855.860.865.865.
870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.865.
865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.
865.865.870.870.870.870.870.870.865.865.865.865.865.870.870.870.870.870.870.870.
875.875.875.875.875.875.875.875.880.880.880.

        15         1.0              (20F4.0)                 1           TOP L3
865.865.865.865.865.865.865.865.860.860.860.860.860.855.855.855.855.860.865.865.
870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.870.865.
865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.865.
865.865.870.870.870.870.870.870.865.865.865.865.865.870.870.870.870.870.870.870.
875.875.875.875.875.875.875.875.880.880.880.

        15         1.0              (20F4.0)                 1           BOTT L3
850.850.850.850.850.850.850.845.845.845.845.845.845.840.840.840.840.845.845.845.
845.845.845.845.845.845.845.845.850.850.850.850.850.850.850.850.845.845.845.845.
845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.
845.845.845.845.845.845.845.845.850.850.850.850.850.850.850.850.850.850.850.850.
850.850.850.850.850.850.850.850.850.855.855.

        15         1.0              (20F4.0)                 1           TOP L4
850.850.850.850.850.850.850.845.845.845.845.845.845.840.840.840.840.845.845.845.
845.845.845.845.845.845.845.845.850.850.850.850.850.850.850.850.845.845.845.845.
845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.845.
845.845.845.845.845.845.845.845.850.850.850.850.850.850.850.850.850.850.850.850.
850.850.850.850.850.850.850.850.850.855.855.

        15         1.0              (20F4.0)                 1           BOTT L4
830 830 830 830 830 830 830 835 840 843 843 843 843 838 838 835 830 830 825 820
820 820 820 820 820 820 825 825 835 835 835 835 835 835 840 840 835 830 830 830
830 830 830 830 830 830 830 830 830 830 830 820 820 820 820 820 820 820 820 820
820 820 820 820 820 820 820 820 820 820 820 820 820 820 820 820 820 820 820 820
820 820 820 820 820 820 815 815 815 815 815

        15         1.0              (20F4.0)                 1           TOP L5
830 830 830 830 830 830 830 835 840 843 843 843 843 838 838 835 830 830 825 820
820 820 820 820 820 820 825 825 835 835 835 835 835 835 840 840 835 830 830 830
830 830 830 830 830 830 830 830 830 830 830 820 820 820 820 820 820 820 820 820
820 820 820 820 820 820 820 820 820 820 820 820 820 820 820 820 820 820 820 820
820 820 820 820 820 820 815 815 815 815 815
```

Listing 6. Input values for the main data file of the particle-tracking post-processing program--Continued

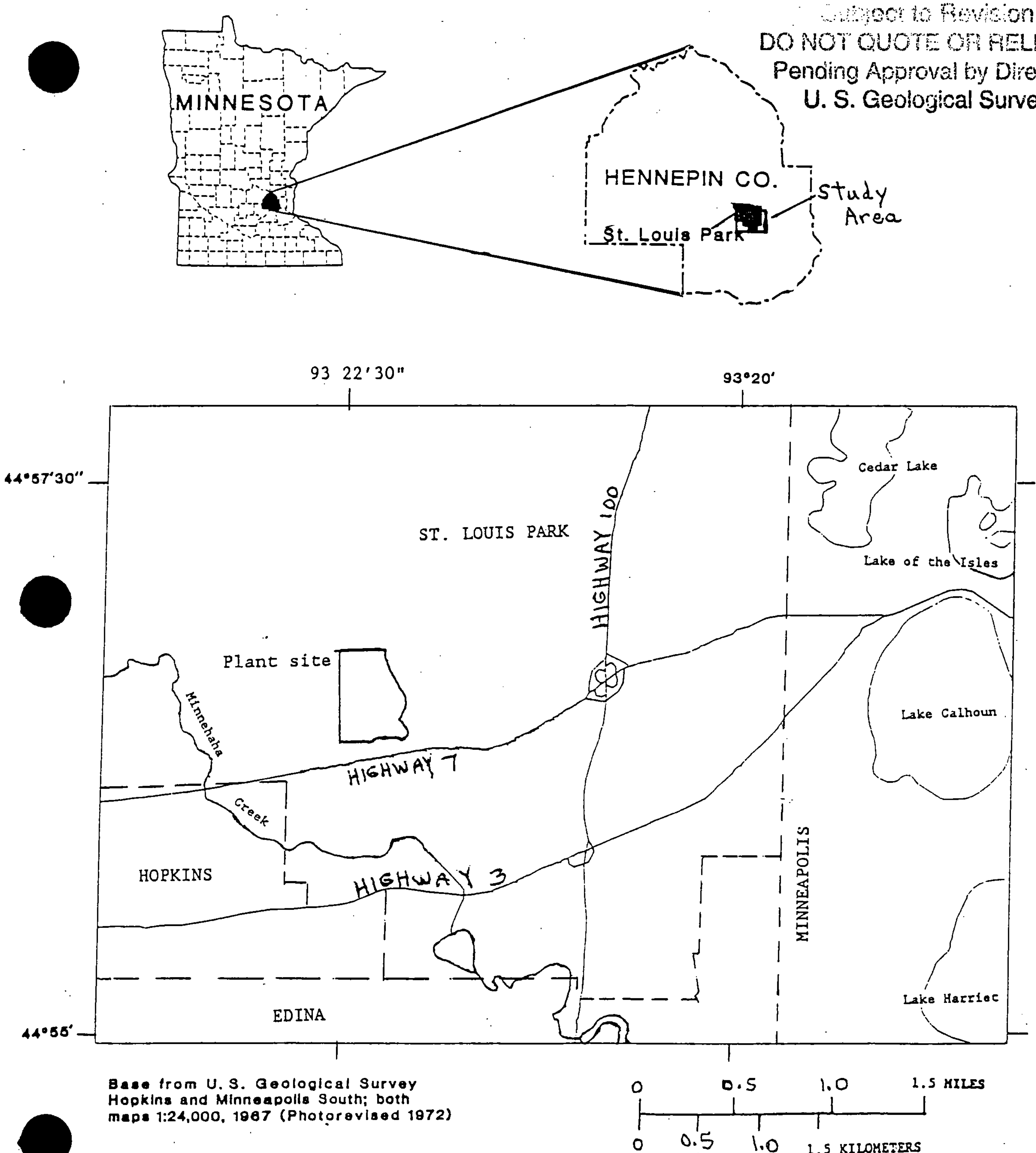
```
        15        1.0               (20F4.0)          1          BOTT L5
825 825 825 825 825 825 820 825 825 823 823 823 823 818 818 820 820 820 815 810
810 810 810 810 810 810 815 815 825 825 825 825 825 825 830 830 825 825 825 825
825 825 825 825 825 820 820 820 820 820 820 810 810 810 810 810 805 800 800 800
800 800 800 800 800 800 800 800 800 800 800 800 805 805 810 810 810 810 810 810
810 810 810 810 810 810 810 810 810 805 805

        15        1.0               (20F4.0)          1          TOP L6
825 825 825 825 825 825 820 825 825 823 823 823 823 818 818 820 820 820 815 810
810 810 810 810 810 810 815 815 825 825 825 825 825 825 830 830 825 825 825 825
825 825 825 825 825 820 820 820 820 820 820 810 810 810 810 810 805 800 800 800
800 800 800 800 800 800 800 800 800 800 800 800 805 805 810 810 810 810 810 810
810 810 810 810 810 810 810 810 810 805 805

        15        1.0               (20F4.0)          1          BOTT L6
800 800 800 800 800 805 800 805 805 808 808 808 808 803 803 805 805 800 795 795
795 795 795 795 795 795 800 800 810 810 810 810 810 810 815 815 810 811 812 813
813 814 814 815 816 812 812 813 813 813 814 804 805 805 805 806 802 798 799 799
799 799 799 799 799 799 799 799 799 799 799 799 795 795 795 790 790 790 790 790
790 790 790 790 790 790 790 790 790 785 785

        15        1.0               (20F4.0)          1          TOP L7
795 795 795 795 795 800 795 800 800 803 803 803 803 798 798 800 800 795 790 790
790 790 790 790 790 790 795 795 805 805 805 805 805 805 810 810 805 806 807 808
808 809 809 810 811 807 807 808 808 808 809 799 800 800 800 801 797 793 794 794
794 794 794 794 794 794 794 794 794 794 794 794 790 790 790 785 785 785 785 785
785 785 785 785 785 785 785 785 785 780 780

        15        1.0               (20F4.0)          1          BOTT L7
670 670 670 670 670 675 670 675 675 678 678 678 678 673 673 675 675 670 665 665
665 665 665 665 665 665 670 670 680 680 680 680 680 680 685 685 680 681 682 683
683 684 684 685 686 682 682 683 683 683 684 674 675 675 675 676 672 668 669 669
669 669 669 669 669 669 669 669 669 669 669 669 665 665 665 660 660 660 660 660
660 660 660 660 660 660 660 660 660 655 655

        15        1.0               (20F4.0)          1                TOP L8
650 650 650 650 650 655 650 655 655 658 658 658 658 653 653 655 655 650 645 645
645 645 645 645 645 645 650 650 660 660 660 660 660 660 665 665 660 661 662 663
663 664 664 665 666 662 662 663 663 663 664 654 655 655 655 656 652 648 649 649
649 649 649 649 649 649 649 649 649 649 649 649 645 645 645 640 640 640 640 640
640 640 640 640 640 640 640 640 640 635 635

        15        1.0               (20F4.0)          1                BOTT L8
610 610 610 610 610 615 610 615 615 618 618 618 618 613 613 615 615 610 605 605
605 605 605 605 605 605 610 610 620 620 620 620 620 620 625 625 620 621 622 623
623 624 624 625 626 622 622 623 623 623 624 614 615 615 615 616 612 608 609 609
609 609 609 609 609 609 609 609 609 609 609 609 605 605 605 600 600 600 600 600
600 600 600 600 600 600 600 600 600 595 595
```

Listing 6. Input values for the main data file of the particle-tracking post-processing program--Continued

```
      15         1          (20I4)         -1       BOUNDARY ARRAY 1
  -1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   0   0   0   0   0   0   0   0   0   0   0

      15         1          (20I4)         -1       BOUNDARY ARRAY 2
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   0   0   0   0   0   0   0   0   0   0   0

      15         1          (20I4)         -1       BOUNDARY ARRAY 3
  -1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1  -1

      15         1          (20I4)         -1       BOUNDARY ARRAY 4
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1

      15         1          (20I4)         -1       BOUNDARY ARRAY 5
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1

      15         1          (20I4)         -1       BOUNDARY ARRAY 6
  -1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1  -1

      15         1          (20I4)         -1       BOUNDARY ARRAY 7
  -1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1  -1

      15         1          (20I4)         -1       BOUNDARY ARRAY 8
  -1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
   1   1   1   1   1   1   1   1   1   1  -1
```

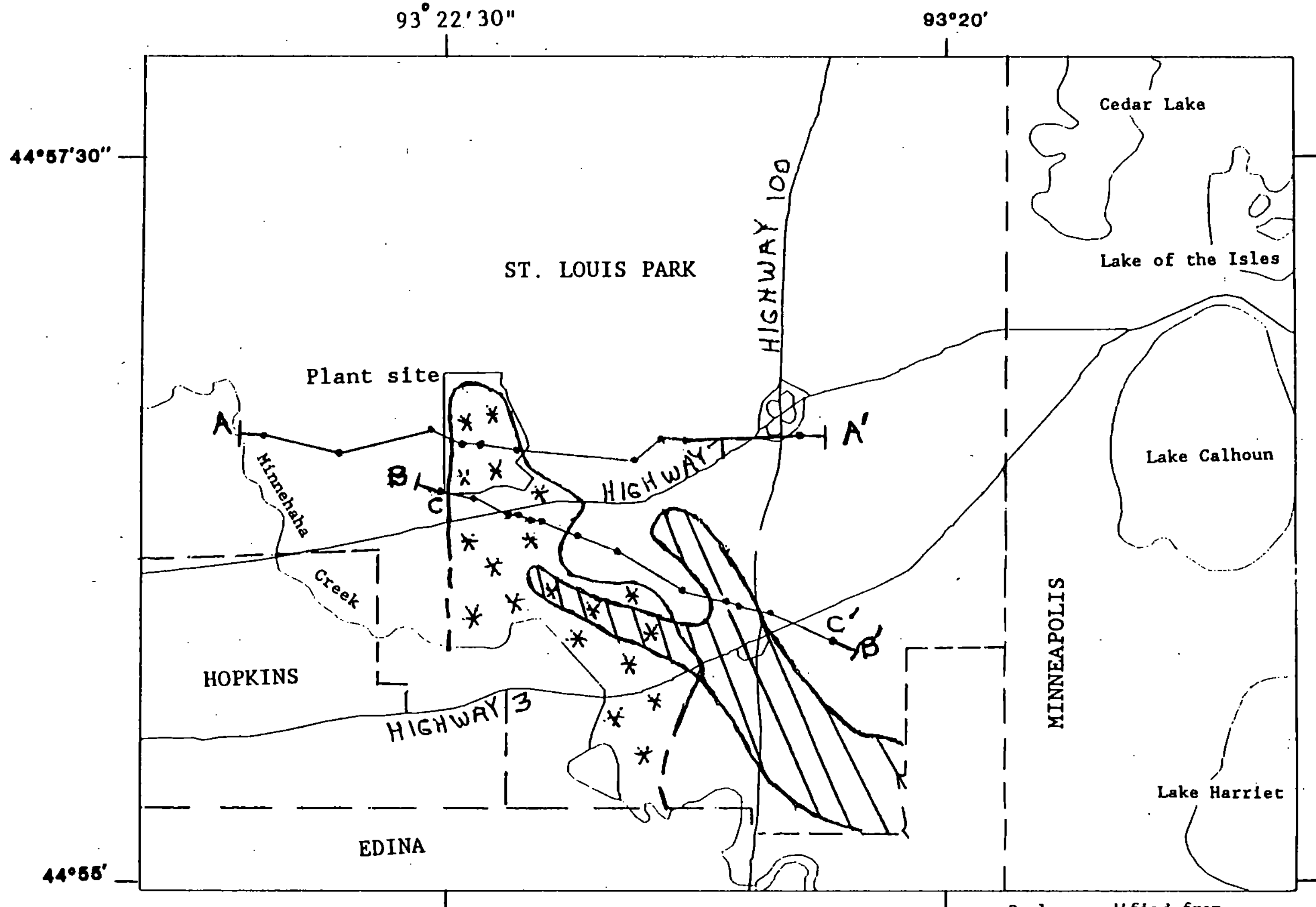
Listing 6. Input values for the main data file of the particle-tracking post-processing program--Continued

```
          15        1.0             (20F4.0)          1                 POROSITY L1
40. 40. 40. 40. 40. 40. 40. 40. 40. 90. 90. 90. 90. 90. 90. 90. 90. 90. 90. 90.
90. 90. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40.
40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40.
40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40.
40. 40. 40. 40. 40. 40. 40. 90. 90. 90. 90.

          15        1.0             (20F4.0)          1                 POROSITY L2
35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35.
35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35.
35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35.
35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35.
35. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40.

          15        1.0             (20F4.0)          1                 POROSITY L3
40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40.
40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40.
40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40.
40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40.
40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40.

          15        1.0             (20F4.0)          1                 POROSITY L4
35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35.
35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35.
35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35.
35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35.
35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35.

          15        1.0             (20F4.0)          1                 POROSITY L5
35. 35. 35. 35. 35. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40. 40.
40. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32.
32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32.
32. 32. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 32. 32. 32. 32. 32. 32. 32. 32.
32. 32. 32. 32. 32. 32. 32. 32. 32. 32. 32.

          15        1.0             (20F4.0)          1                 POROSITY L6
26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26.
26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26.
26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26.
26. 26. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35. 26. 26. 26. 26. 26. 26. 26. 26.
26. 26. 26. 26. 26. 26. 26. 26. 26. 26. 26.

          15        1.0             (20F4.0)          1                 POROSITY L67
 5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.
 5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.
 5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.
 5.  5. 35. 35. 35. 35. 35. 35. 35. 35. 35. 35.  5.  5.  5.  5.  5.  5.  5.  5.
 5.  5.  5.  5.  5.  5.  5.  5.  5.  5.  5.

           0        25.                                                 POROSITY L7
           0         5.                                                 POROSITY L78
           0        31.                                                 POROSITY L8
```



Base from U. S. Geological Survey
Hopkins and Minneapolis South; both
maps 1:24,000, 1967 (Photorevised 1972)

Figure 1.--Location of study area, St. Louis Park, and plant site in the Minneapolis-St. Paul Metropolitan Area



Base from U. S. Geological Survey Hopkins and Minneapolis South; both maps 1:24,000, 1967 (Photorevised 1972)

Geology modified from Olsen and Bloomgren, 1989, Minnesota Geological Survey

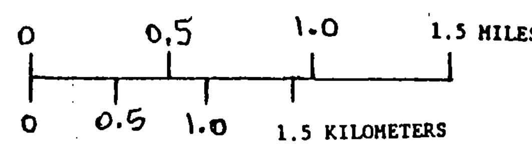


Figure 2.--Trace of hydrogeologic sections and location of plant site, bedrock valleys, and peat areas

EXPLANATION

** AREA UNDERLAIN MAINLY BY PEAT--Dashed where approximate

BEDROCK VALLEYS--Area where Platteville aquifer is absent and drift is underlain by St. Peter aquifer

A——A' TRACE OF GEOLOGIC SECTION

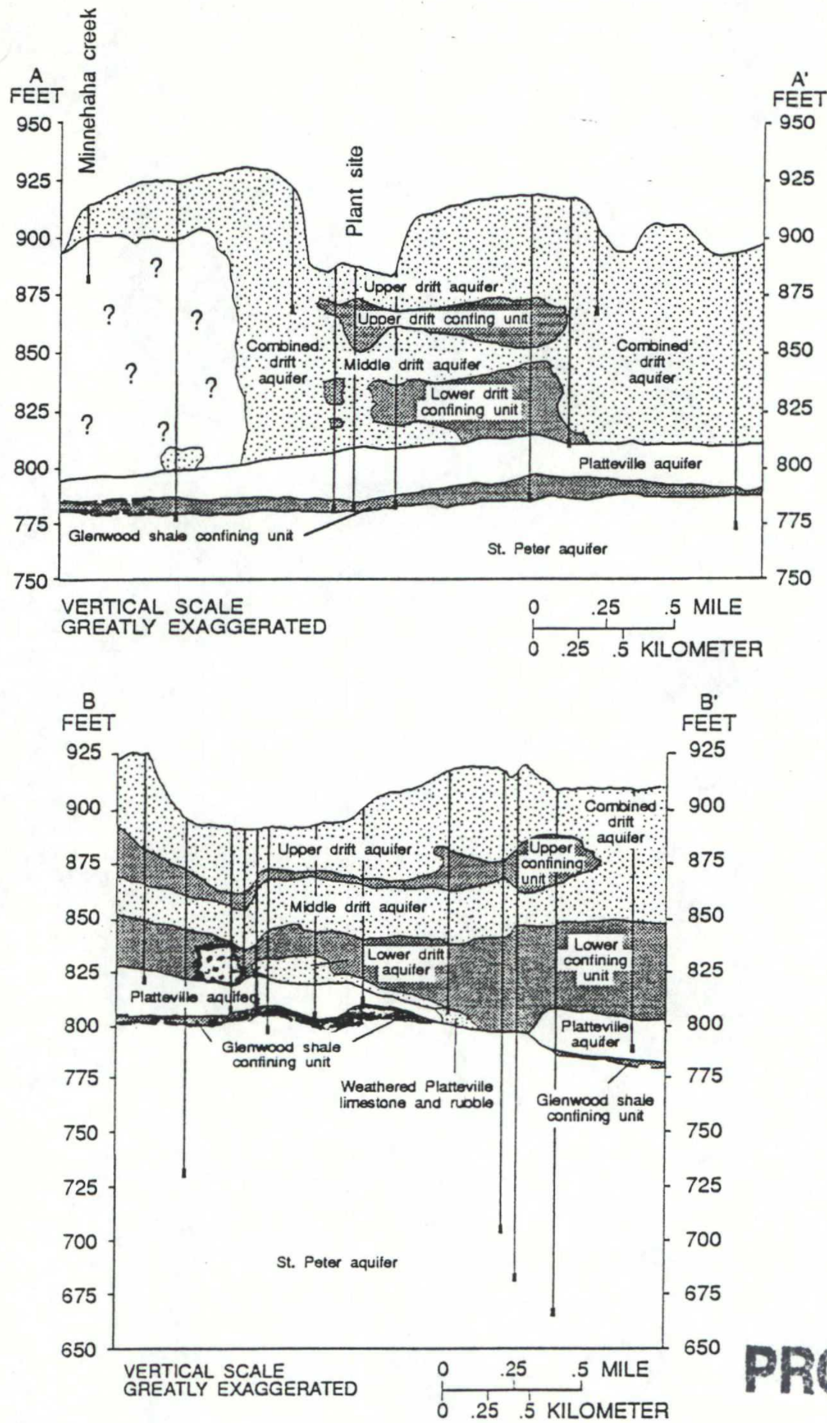


Figure 3.--Hydrogeology section showing hydrogeologic units (trace of sections shown in figure 2).

EXPLANATION

GLACIAL-DRIFT AQUIFER

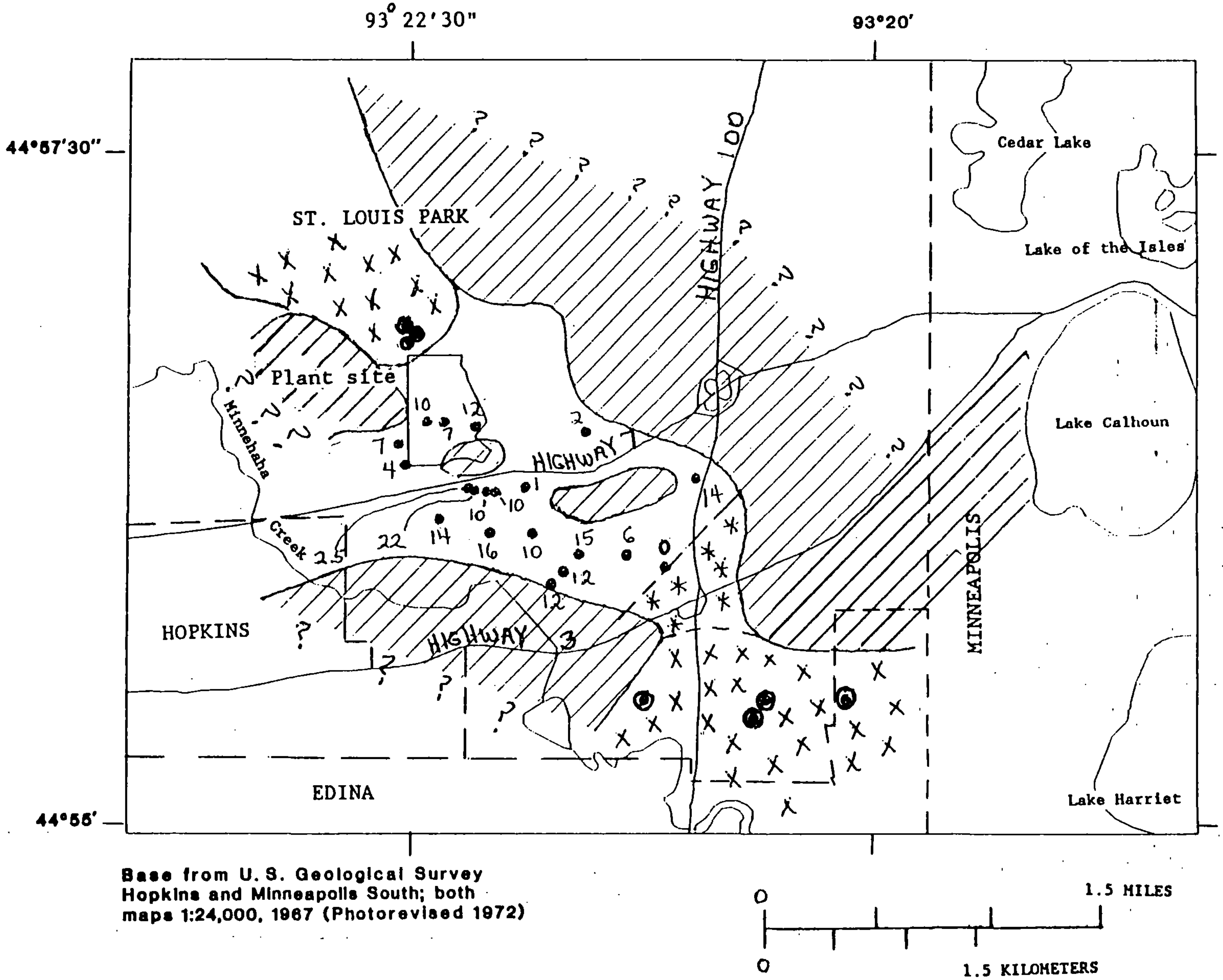
UNKNOWN LITHOLOGY, NO TEST HOLE INFORMATION AVAILABLE

CONFINING UNIT

BEDROCK AQUIFER

WELL OR TEST HOLE

CONTACT--Dashed where inferred



Base from U. S. Geological Survey
Hopkins and Minneapolis South; both
maps 1:24,000, 1967 (Photorevised 1972)

Figure 4.--Saturated thickness of upper drift aquifer

EXPLANATION

UPPER DRIFT CONFINING UNIT IS ABSENT. UPPER AND MIDDLE DRIFT AQUIFERS COMPRISE A CONTINUOUS UNCONFINED AQUIFER--A ? indicates sufficient data is not available beyond patterned area to determine extent of upper drift confining unit.

UPPER DRIFT AQUIFER IS ABSENT. UPPER DRIFT CONFINING UNIT IS PRESENT AT LAND SURFACE.

UNSATURATED SAND AND GRAVEL IS PRESENT AT LAND SURFACE. WATER TABLE IS AT OR BELOW TOP OF UPPER DRIFT CONFINING UNIT.

TEST HOLE

16 Number is saturated thickness of aquifer, in feet

Aquifer is absent, with till or clay present at land surface

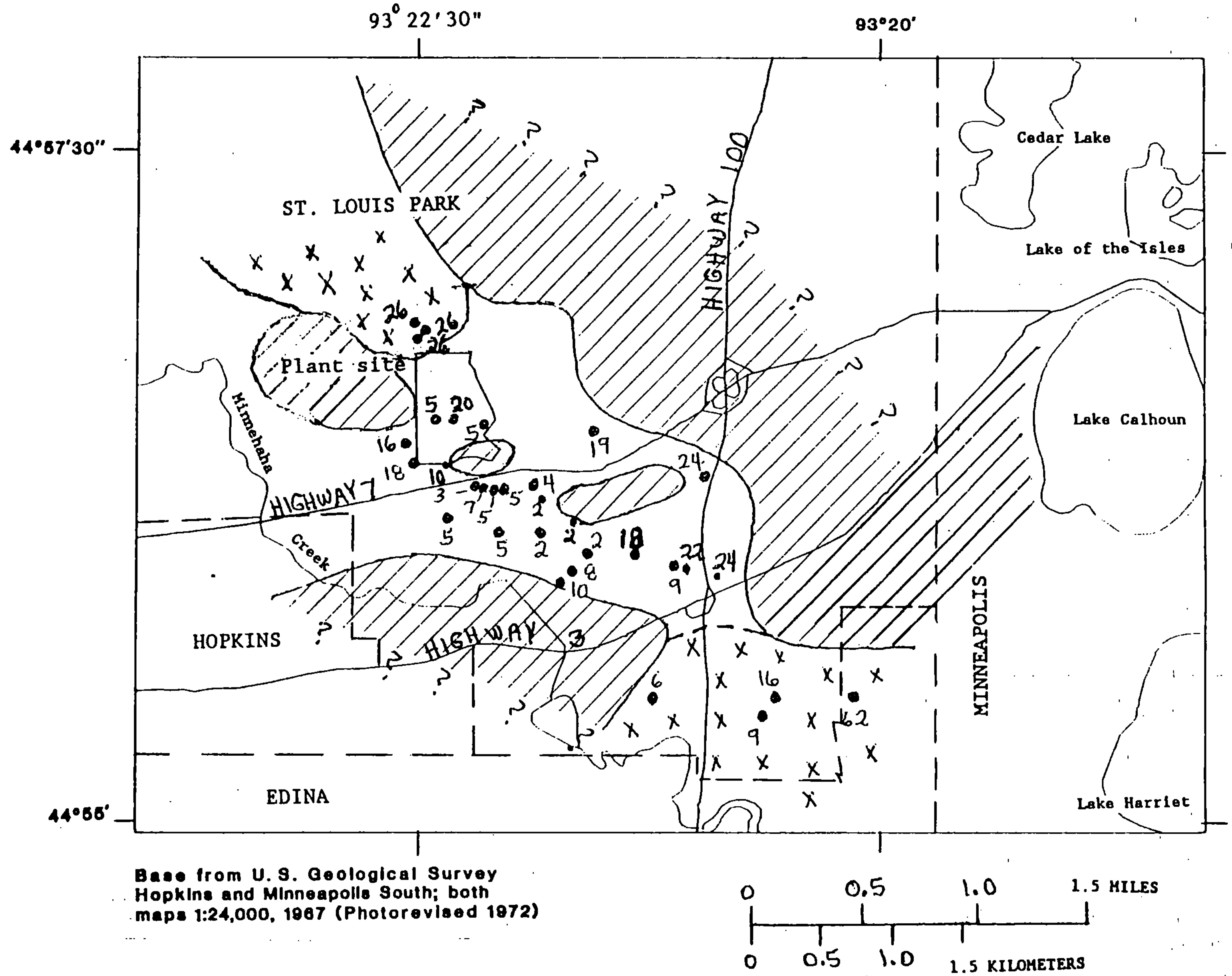


Figure 5. Thickness of upper drift confining unit

EXPLANATION

UPPER DRIFT CONFINING UNIT IS ABSENT. UPPER AND MIDDLE DRIFT AQUIFERS COMPRISE A CONTINUOUS UNCONFINED AQUIFER--A ? indicates sufficient data is not available beyond patterned area to determine extent of upper drift confining unit.

X X UPPER DRIFT AQUIFER IS ABSENT. UPPER DRIFT CONFINING UNIT IS PRESENT AT LAND SURFACE.

16 TEST HOLE--Number is thickness of upper drift confining unit, in feet

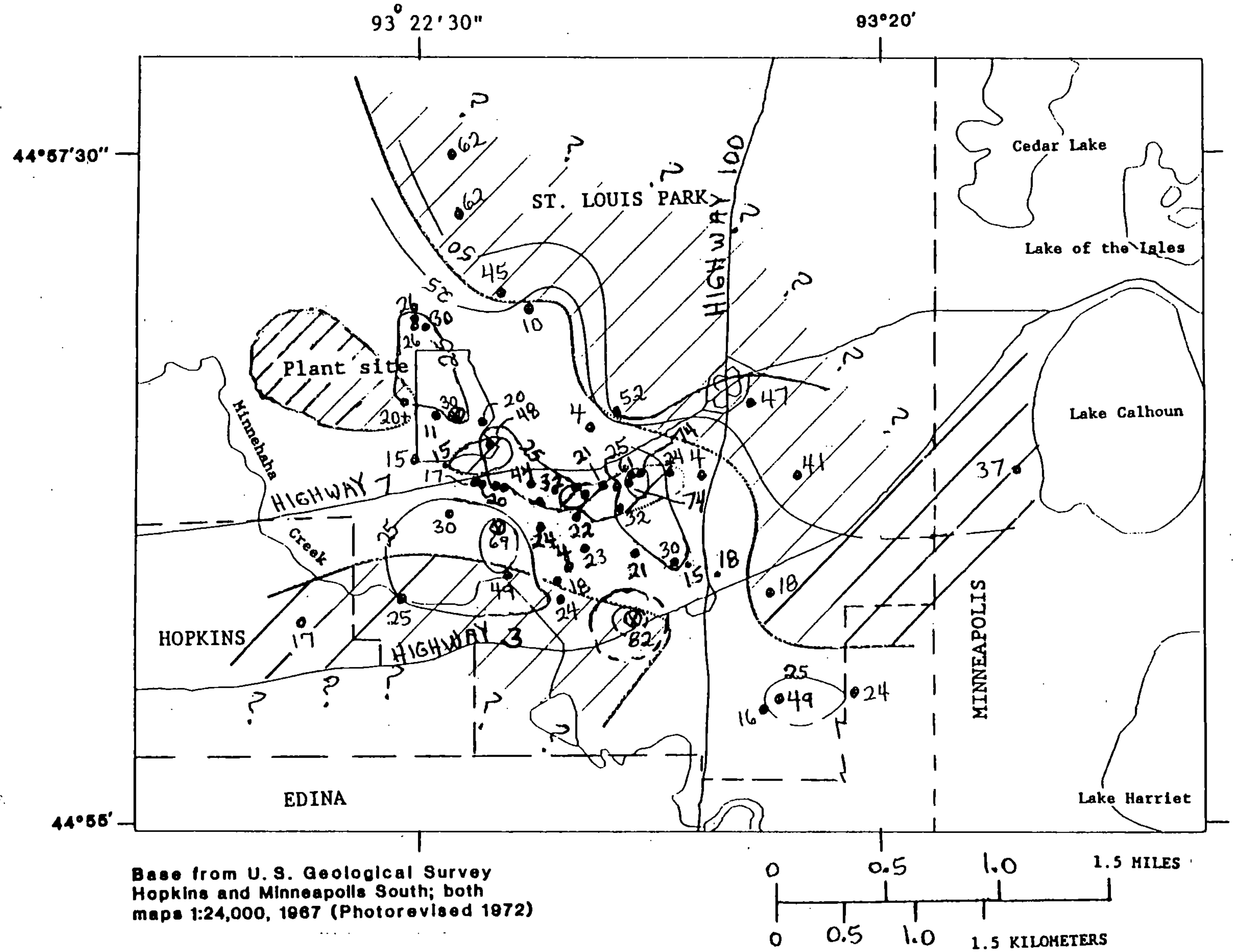


Figure 6.--Saturate ckness of middle drift aquifer

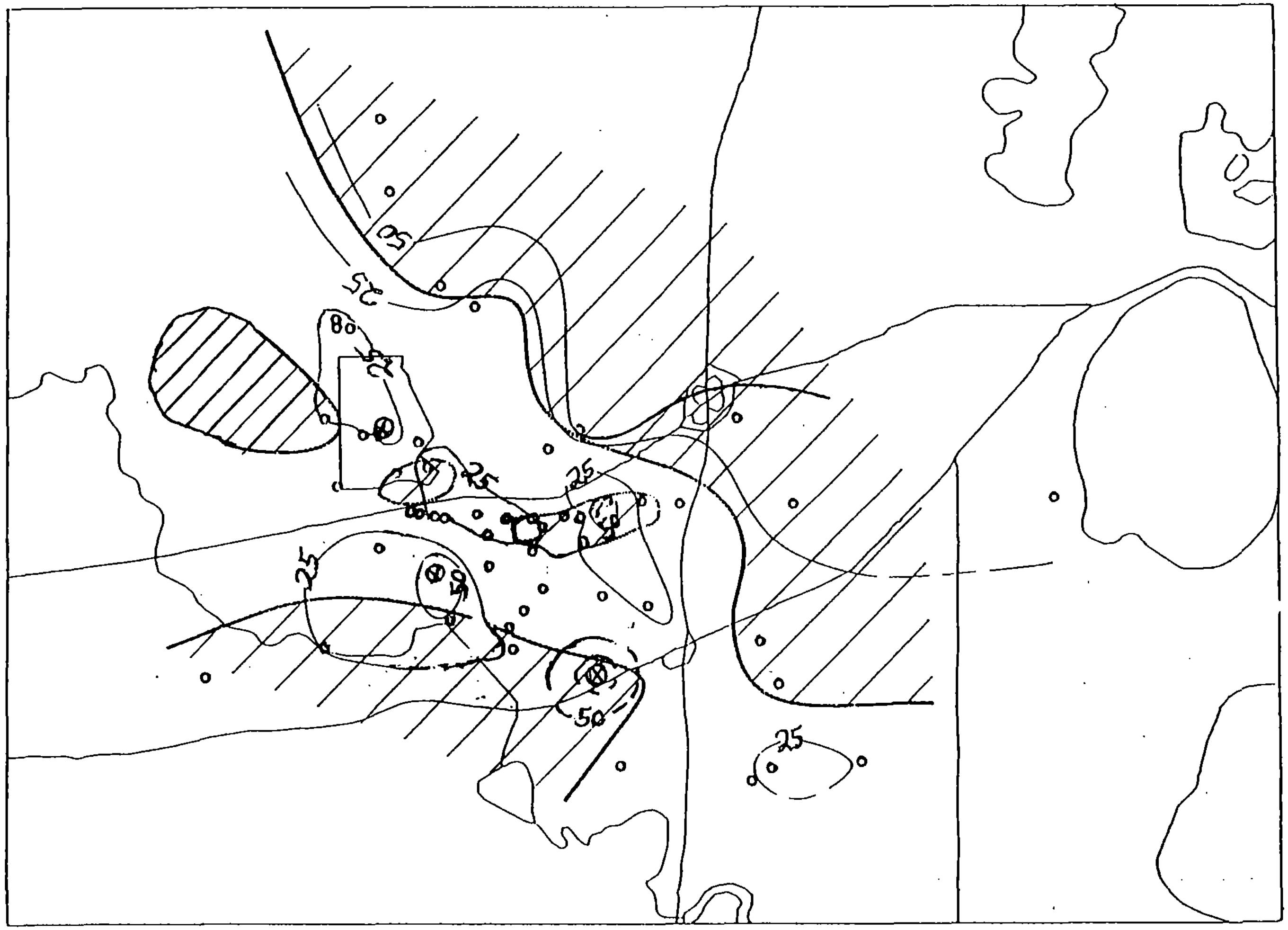


Fig. 6 with data points, but no data values (less cluttered)

EXPLANATION

UPPER DRIFT CONFINING UNIT IS ABSENT. UPPER AND MIDDLE DRIFT AQUIFERS COMPRISE A CONTINUOUS UNCONFINED AQUIFER--A ? indicates sufficient data is not available beyond patterned area to determine extent of upper drift confining unit.

——25-- LINE OF EQUAL THICKNESS OF MIDDLE DRIFT AQUIFER--Dashed where approximate. Contour interval 25 feet

TEST HOLE

20+ • Number is saturated thickness of middle drift aquifer, in feet. A plus (+) indicates that the hole did not penetrate to the bottom of the aquifer.

⊗ No confining unit present between the middle drift and lower drift aquifers; sand and gravel unit extends downward to the bedrock surface

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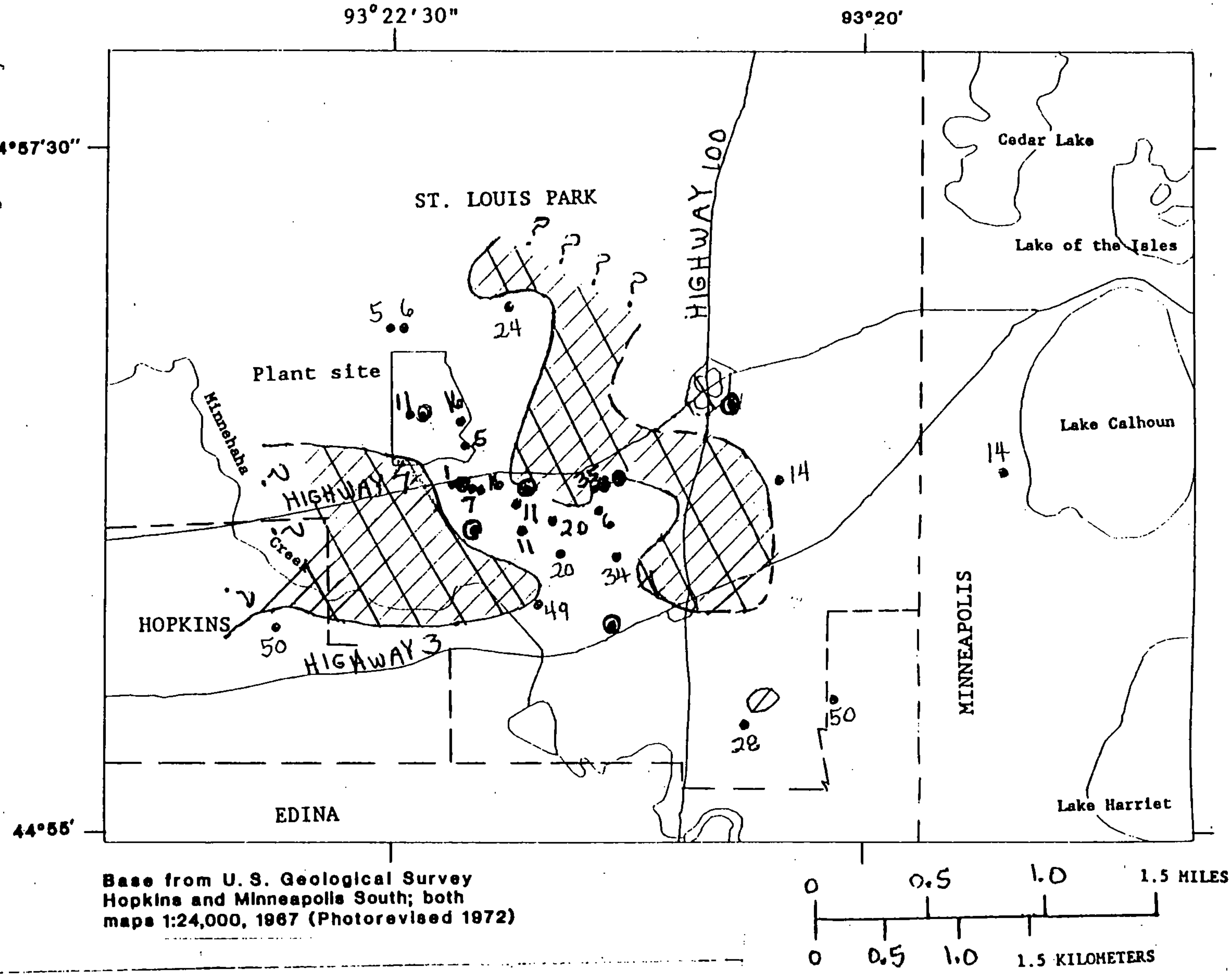


Figure 7.--Thickness of lower drift confining unit

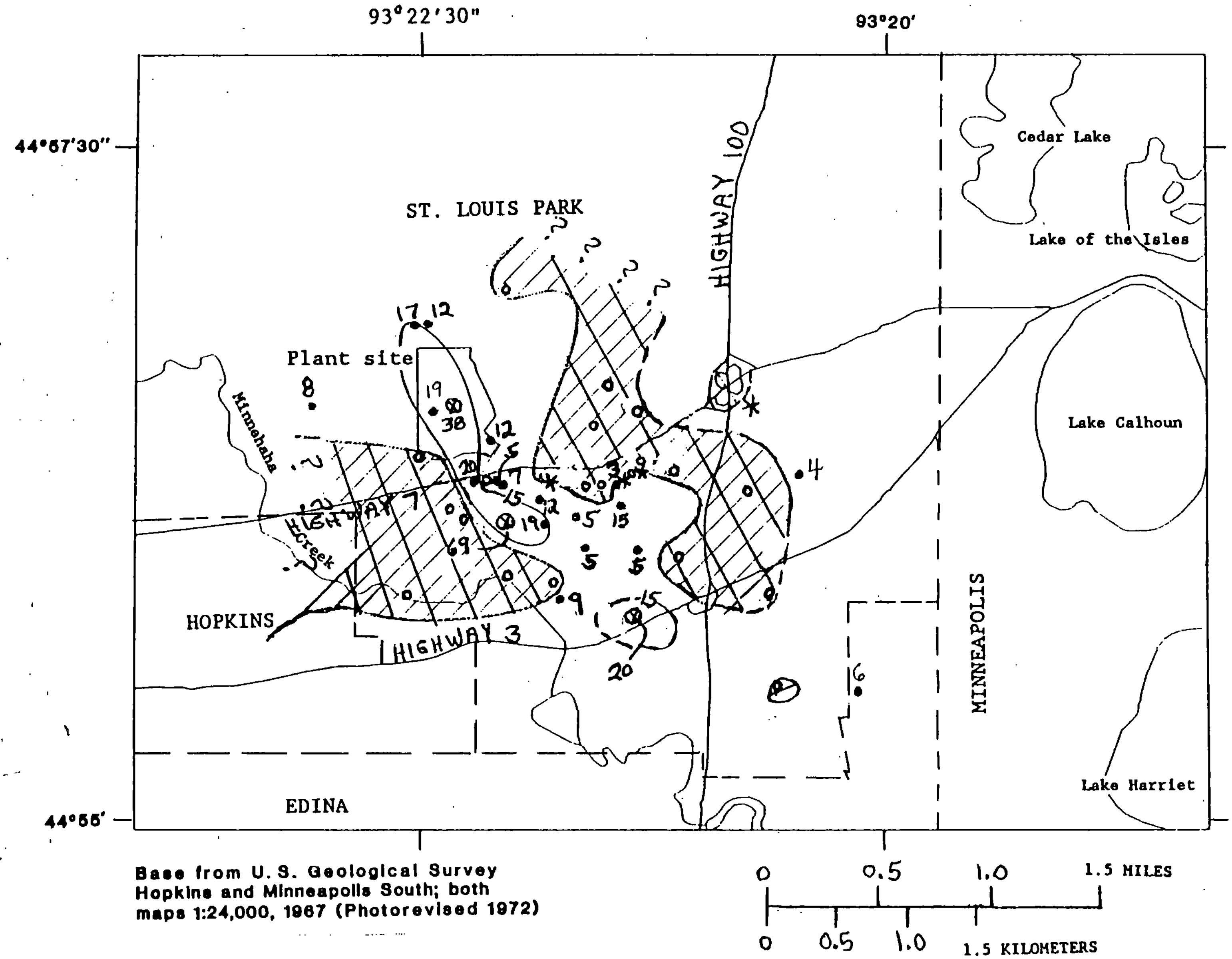
EXPLANATION

LOWER DRIFT AQUIFER IS ABSENT--Dashed where approximate. A ? indicates sufficient data is not available beyond patterned area to determine if lower drift aquifer is absent.

TEST HOLE

16 Number is thickness of lower drift confining unit, in feet

Confining unit is absent



Base from U. S. Geological Survey
Hopkins and Minneapolis South; both
maps 1:24,000, 1967 (Photorevised 1972)

Figure 8.--Saturated t[illegible]ness of lower drift aquifer

EXPLANATION

LOWER DRIFT AQUIFER IS ABSENT--Dashed where approximate. A ? indicates sufficient data is not available beyond patterned area to determine if lower drift aquifer is absent.

——15-- LINE OF EQUAL THICKNESS OF LOWER DRIFT AQUIFER--Dashed where approximate. Contour interval is variable

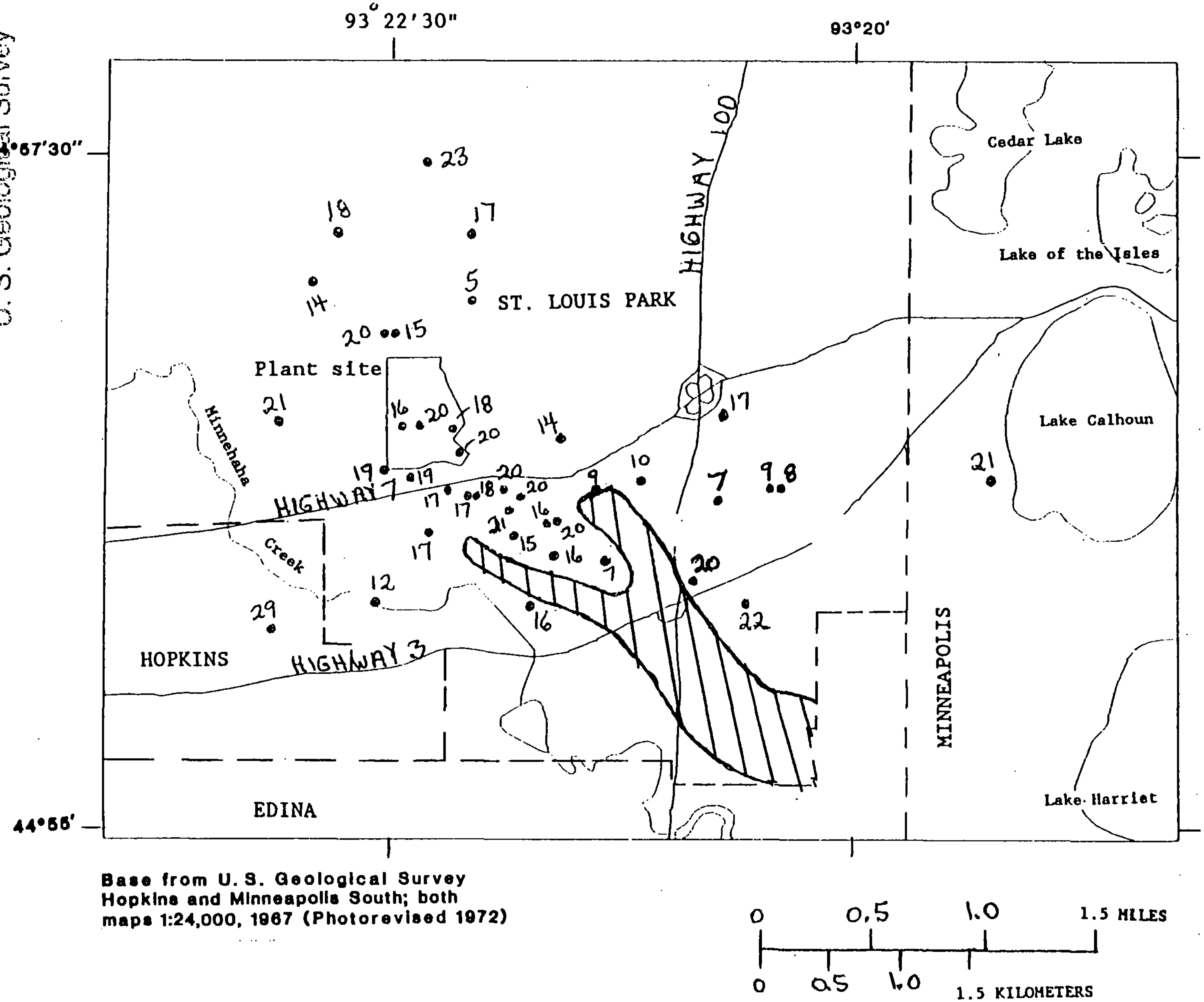
TEST HOLE

17 Number is saturated thickness of lower drift aquifer, in feet

No confining unit present between the middle drift and lower drift aquifers; sand and gravel unit extends downward to the bedrock surface

Sand and gravel extends from the land surface downward to the bedrock surface, with no intervening confining units

Lower drift aquifer is absent



Base from U. S. Geological Survey Hopkins and Minneapolis South; both maps 1:24,000, 1967 (Photorevised 1972)

Figure 9.--Thickness [illegible] Platteville aquifer

EXPLANATION

BEDROCK VALLEYS--Area where Platteville aquifer is absent and drift is underlain by St. Peter aquifer

16

TEST HOLE--Number is thickness of Platteville aquifer, in feet

Upper and middle drift aquifers
December 1987

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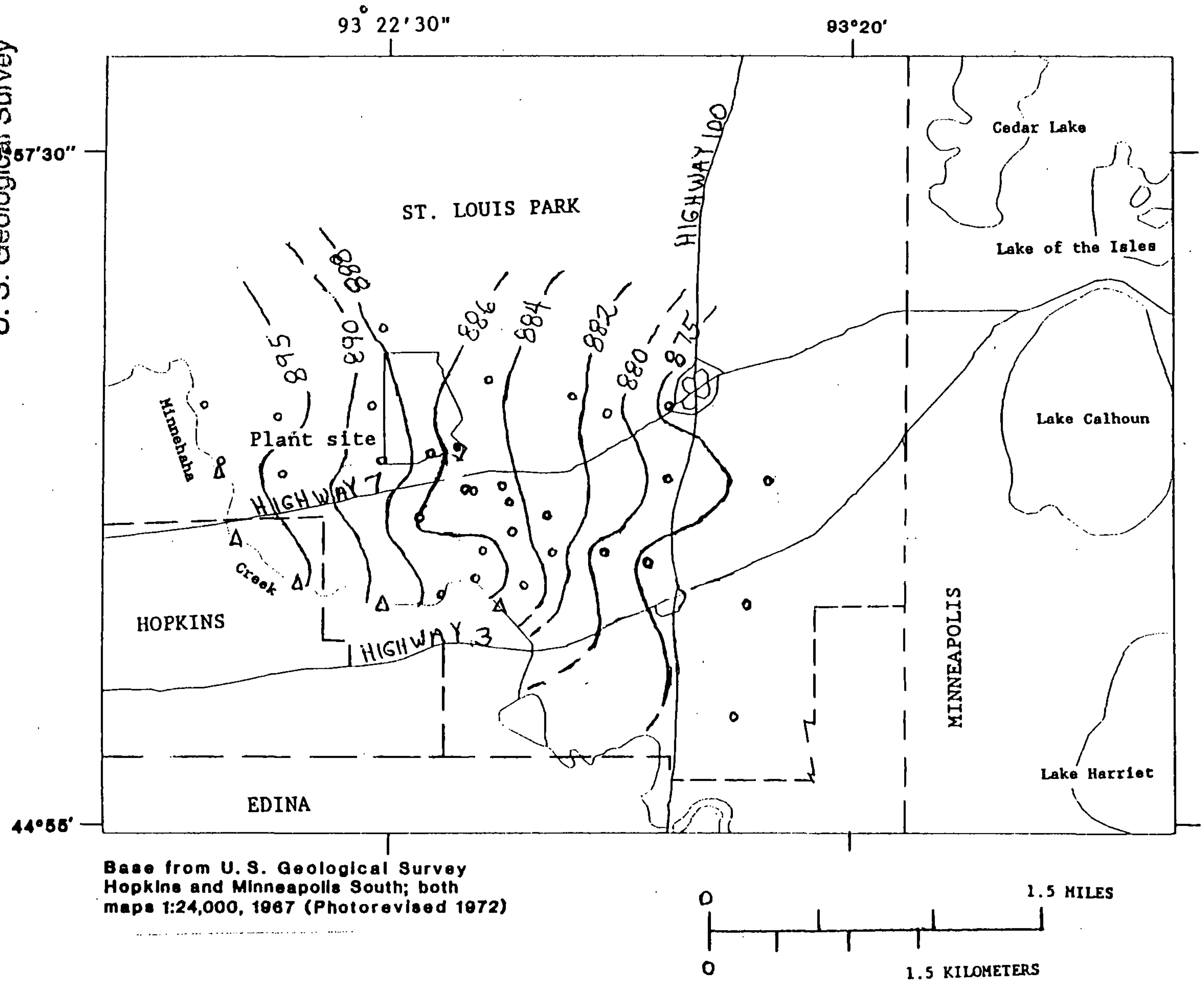
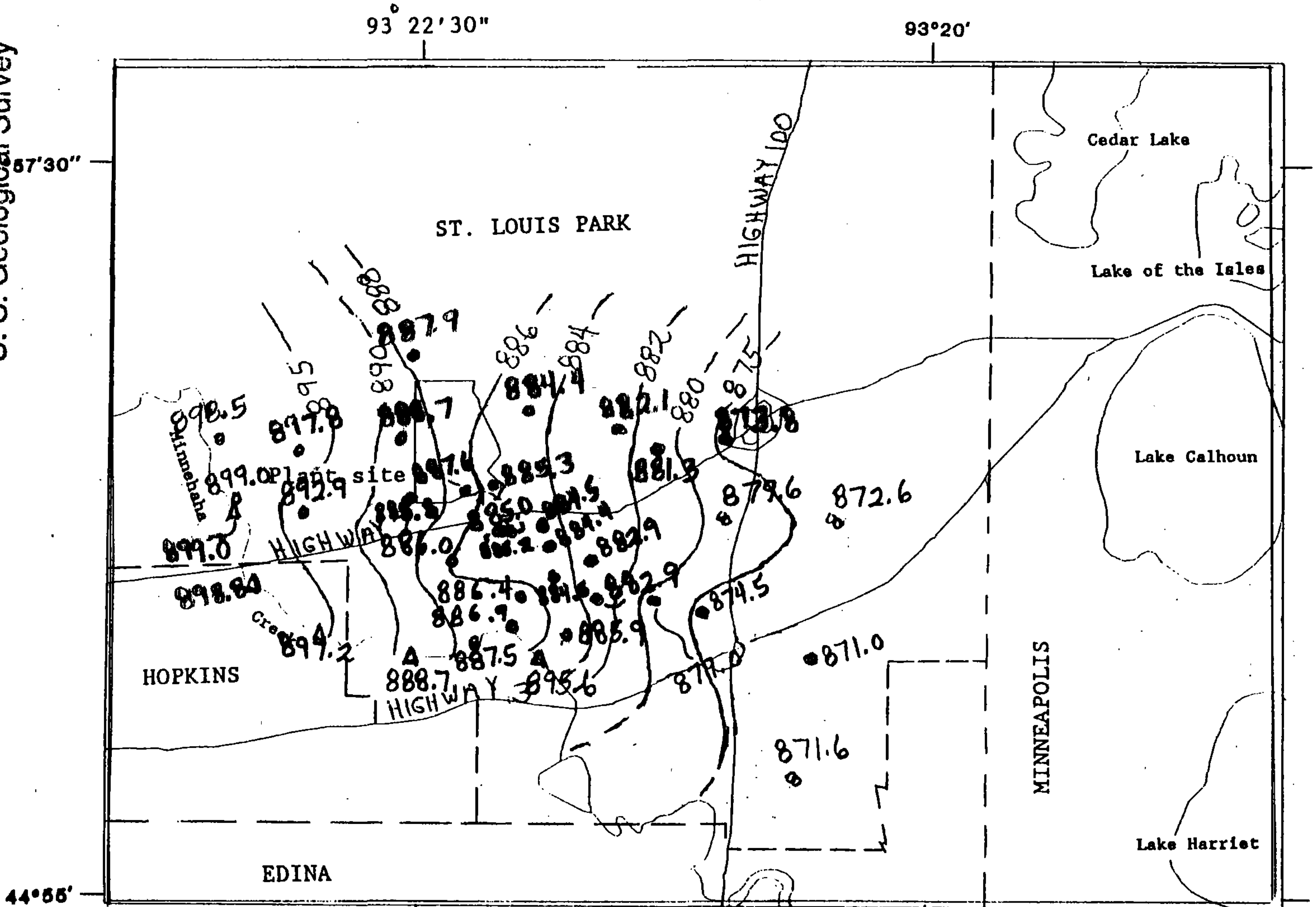


Figure 10.--Composite potentiometric surface of the upper and middle drift aquifers, December 1987



Base from U. S. Geological Survey
Hopkins and Minneapolis South; both
maps 1:24,000, 1967 (Photorevised 1972)

OVER LAY FOR FIGURE 10

0 1.5 MILES
1.5 KILOMETERS

Figure 10.--Composite potentiometric surface of the upper and middle drift aquifers, December 1987

Figure 10.--Composite potentio 'c surface of the upper and middle drift aquifers, De r 1987

EXPLANATION

—890--	POTENTIOMETRIC CONTOUR--Shows line of equal altitude at which water levels would stand in tightly cased wells. Dashed where approximate. Contour interval is variable
886.4 ○	OBSERVATION WELL--Number is altitude of water surface, in feet
897.2 △	STREAM-STAGE MEASUREMENT LOCATION--Number is altitude of stream water surface, in feet

NOTE; DATUM IS SEA LEVEL

EXPLANATION

BEDROCK VALLEYS--Area where Platteville aquifer is absent and drift is underlain by St. Peter aquifer

——890-- POTENTIOMETRIC CONTOUR--Shows line of equal altitude at which water levels would stand in tightly cased wells. Dashed where approximate. Contour interval is variable

885.2

o OBSERVATION WELL--Number is altitude of water surface, in feet

NOTE; DATUM IS SEA LEVEL

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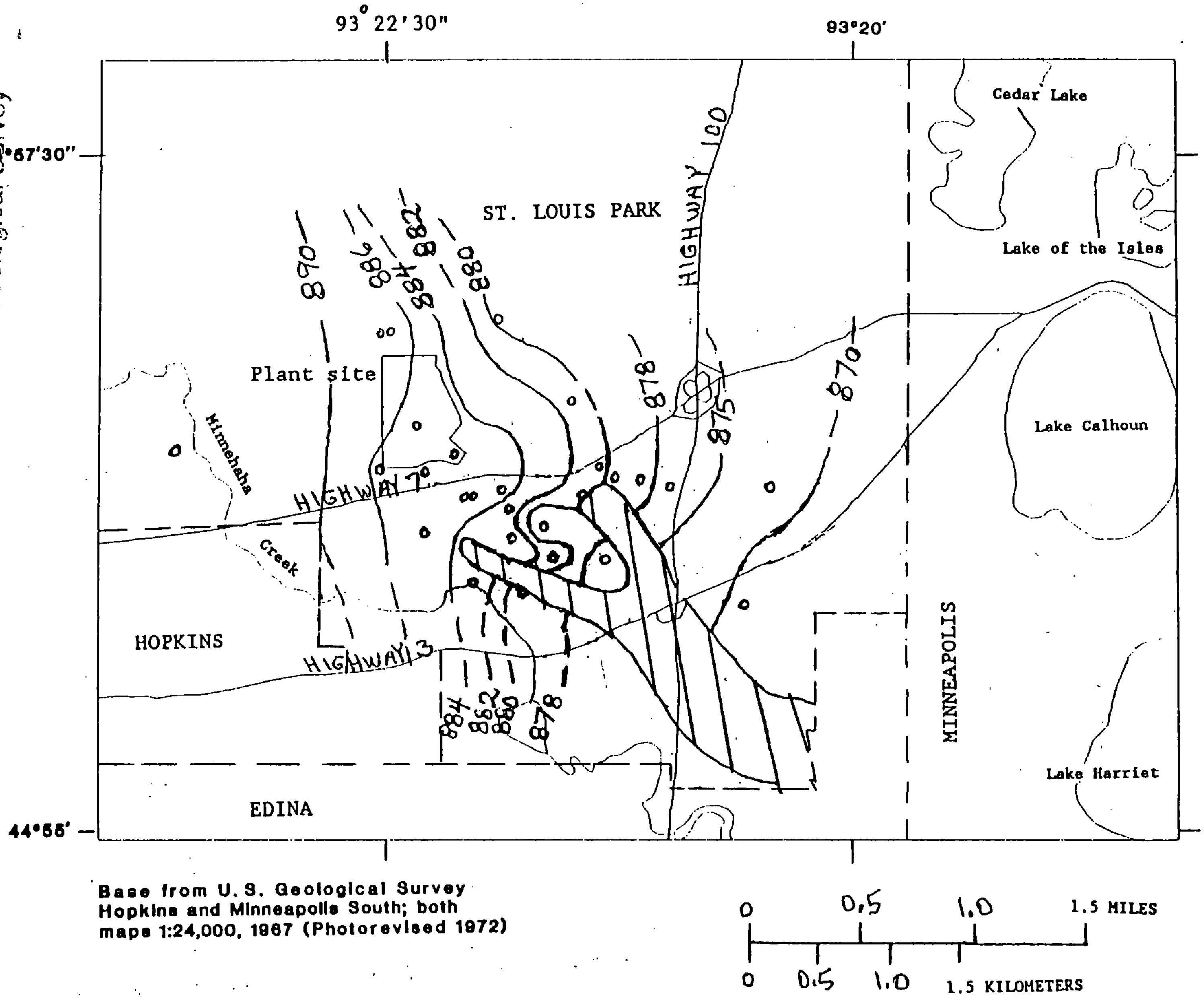

Figure 11.--Potentiometric surface of the Platteville aquifer, December 1987

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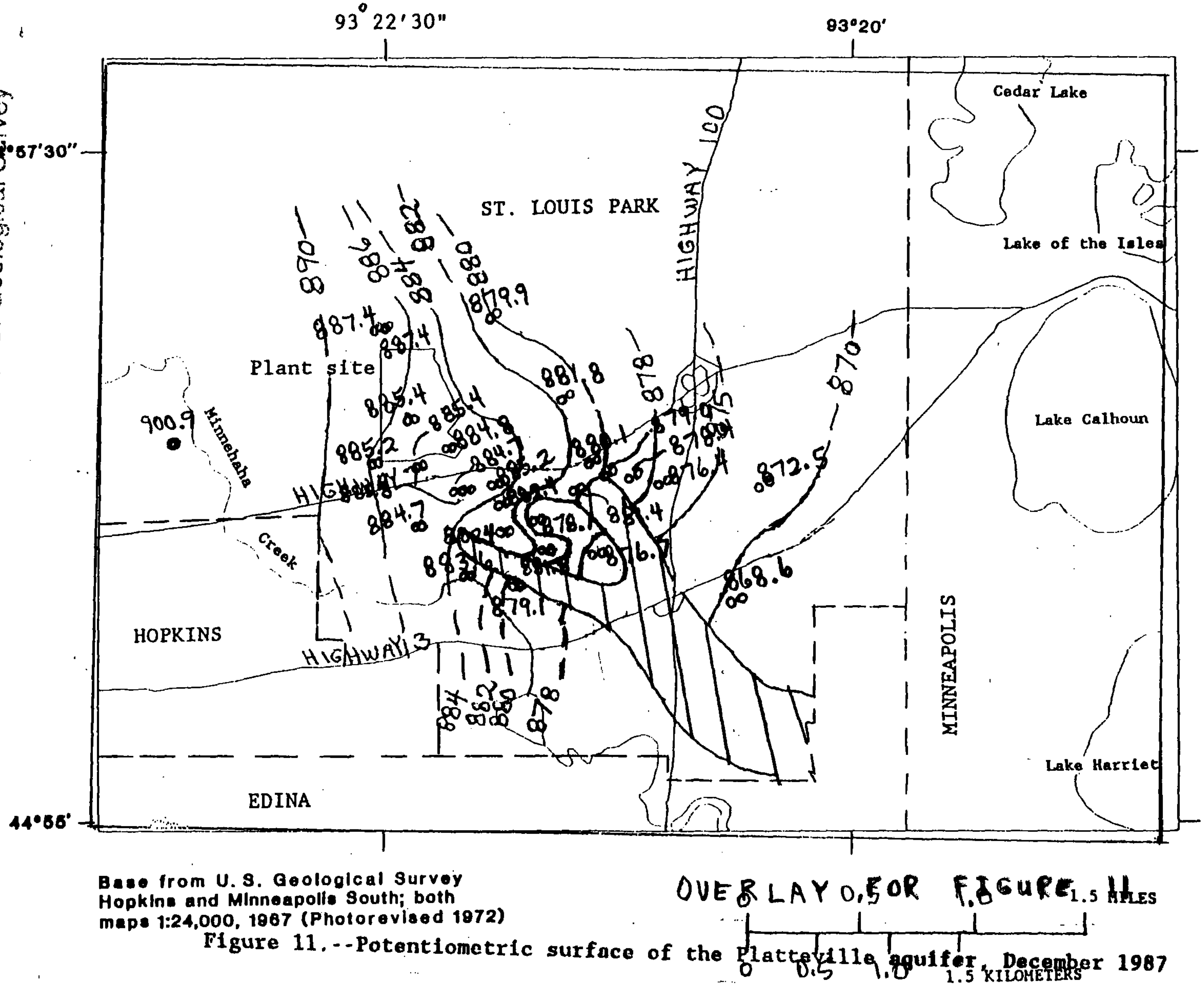
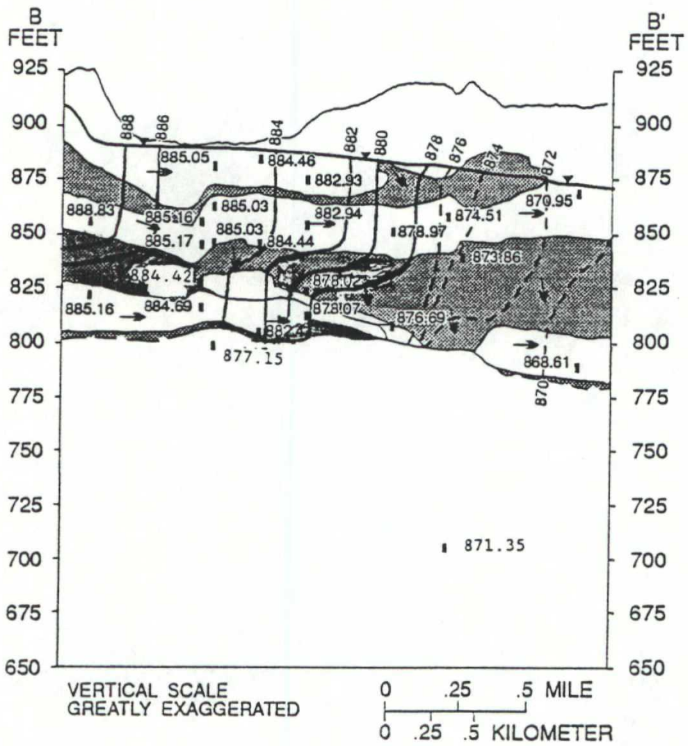


Base from U. S. Geological Survey Hopkins and Minneapolis South; both maps 1:24,000, 1967 (Photorevised 1972)

Figure 11.--Potentiometric surface of the Platteville aquifer, December 1987

Figure 11.--Potentiometric surface of the Platteville aquifer, December 1987



EXPLANATION

Confining unit

Aquifer

Equipotential line, dashed where approximate

Water-table

Ground-water flow

Screened intervals, number indicates hydraulic head

Figure 12.--Hydrogeology section showing hydraulic heads in December 1987, equipotential lines, and direction of ground-water flow (trace of section shown in figure 2).

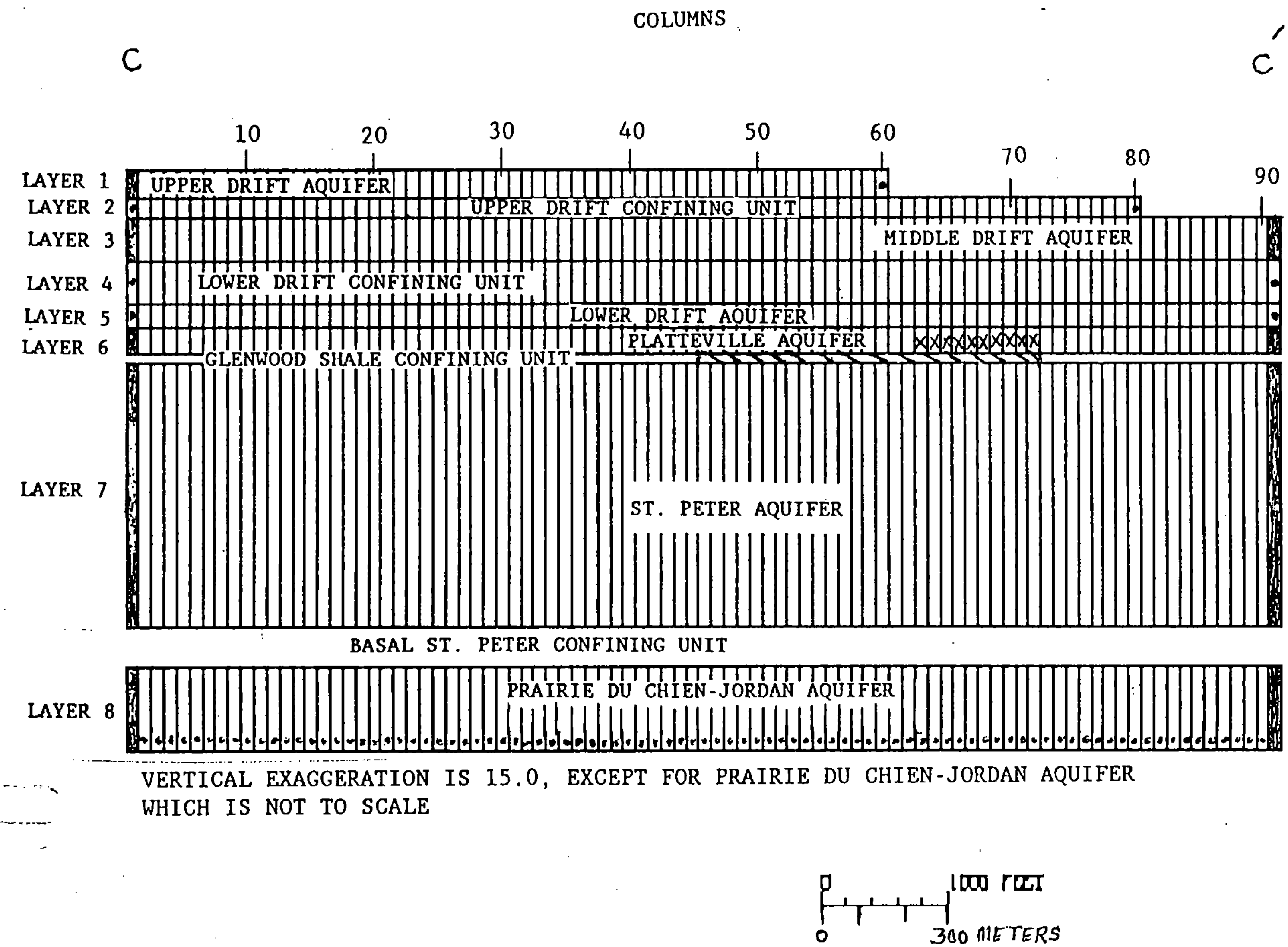


Figure 13.--Hydrogeologic units and cross-section model layers (trace of section shown in fig. 2)

EXPLANATION

AREA WHERE GLENWOOD SHALE CONFINING UNIT IS ABSENT OR DISCONTINUOUS

SPECIFIED-HEAD BOUNDARY CELL

NO-FLOW BOUNDARY CELL

X BEDROCK VALLEY

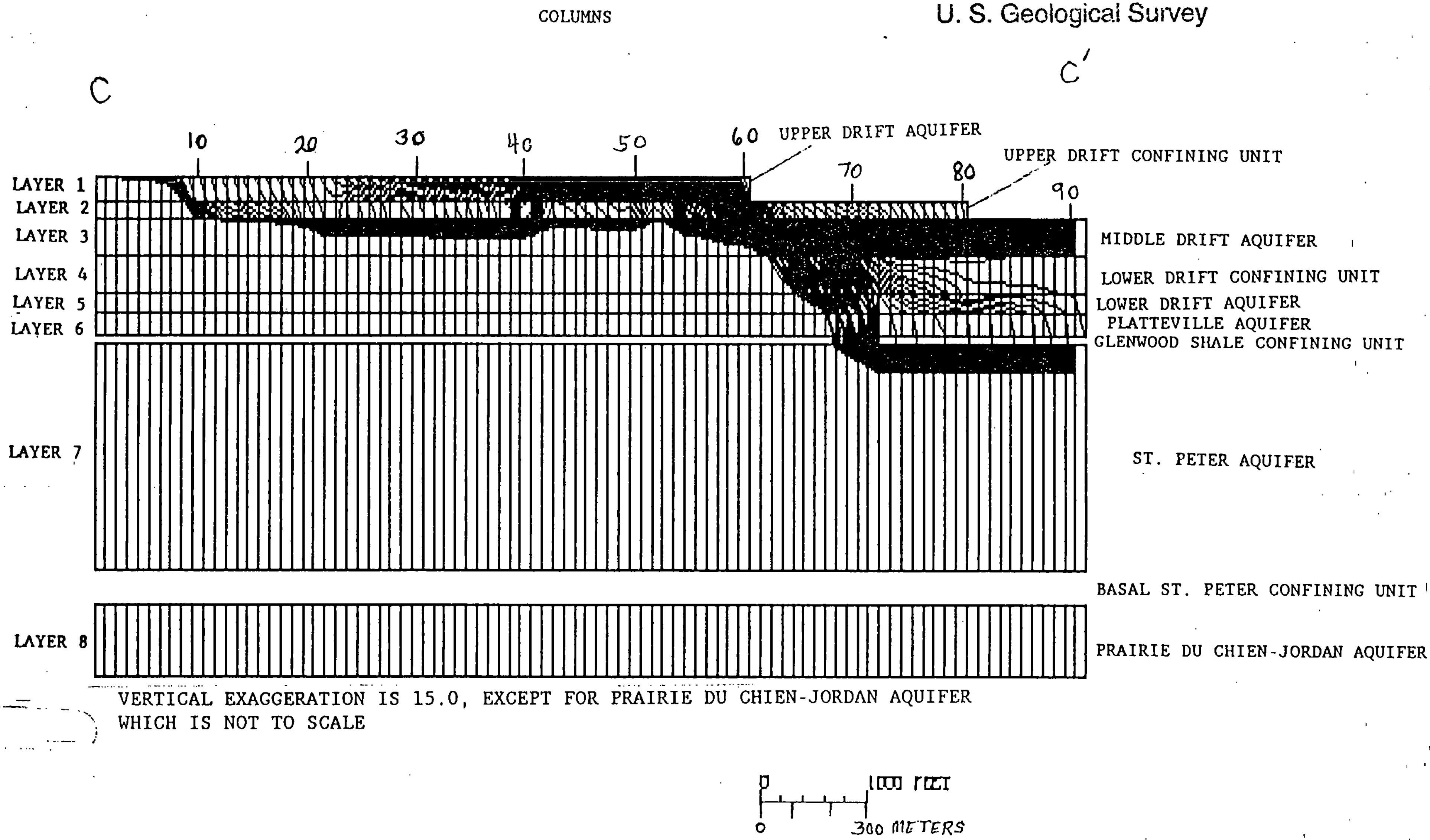


Figure 14.--Path-line plot representing movement through the aquifer system of recharge water derived from t[illegible]nfiltration of precipitation (trace of section shown in fig. [illegible]

EXPLANATION

PARTICLE PATH LINES--Forward-tracking from the recharge (land) surface. Solid areas result from the convergence of path lines

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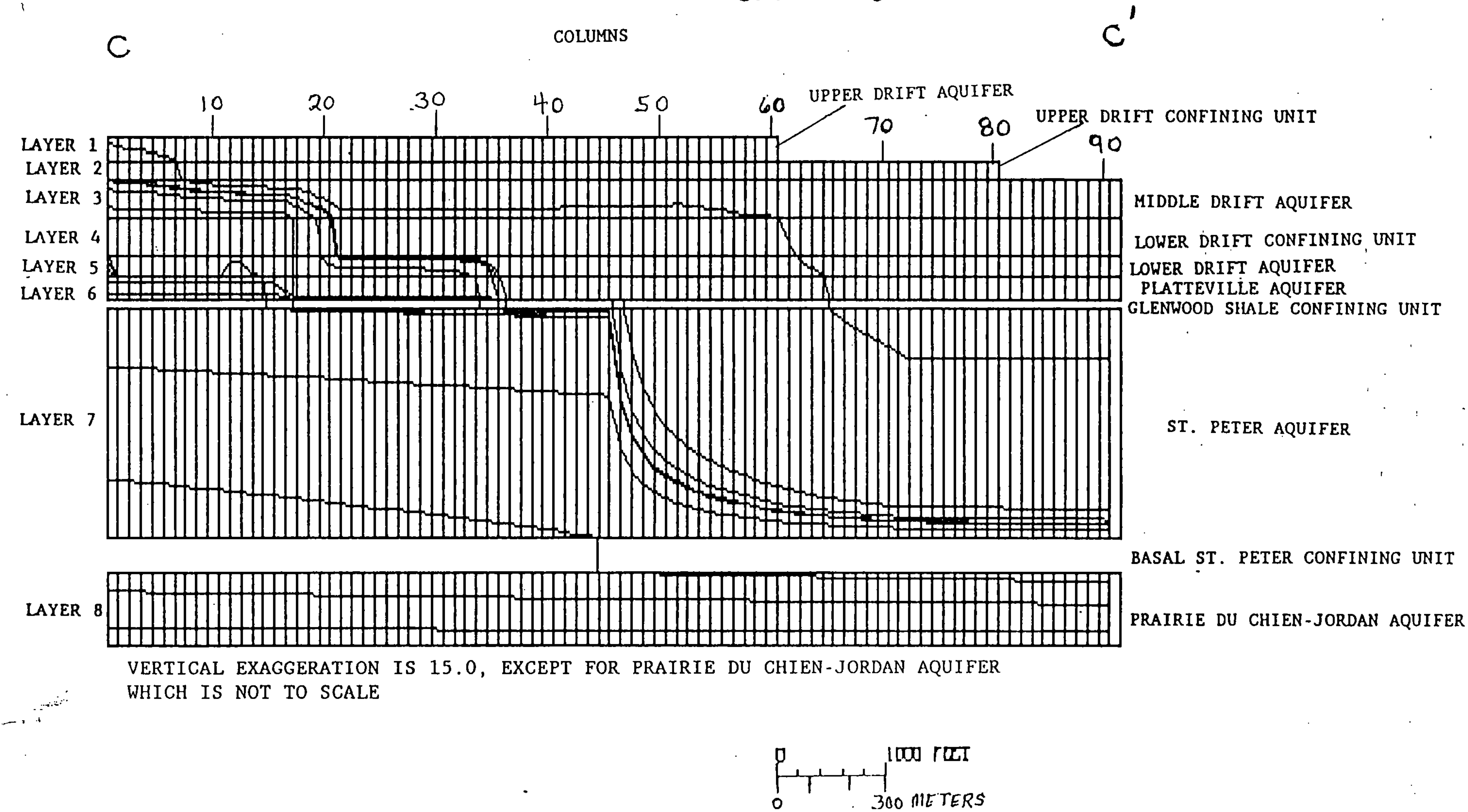


Figure 15.--Path-line plot representing movement through the aquifer system of water derived from boundary inf[illegible] (trace of section shown in fig. 2)

EXPLANATION

PARTICLE PATH LINES--Forward-tracking from western boundary. Solid areas result from the convergence of path lines

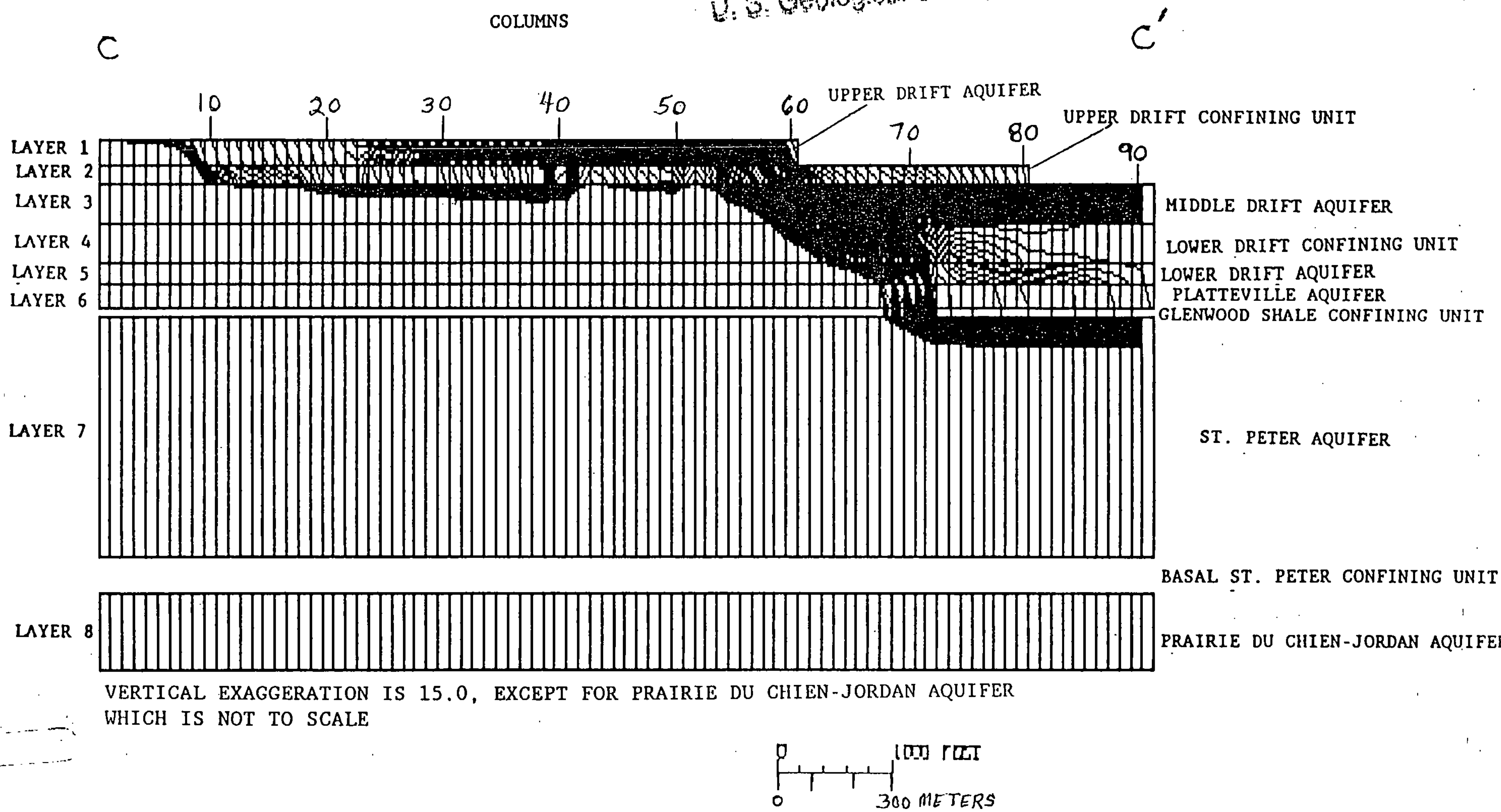
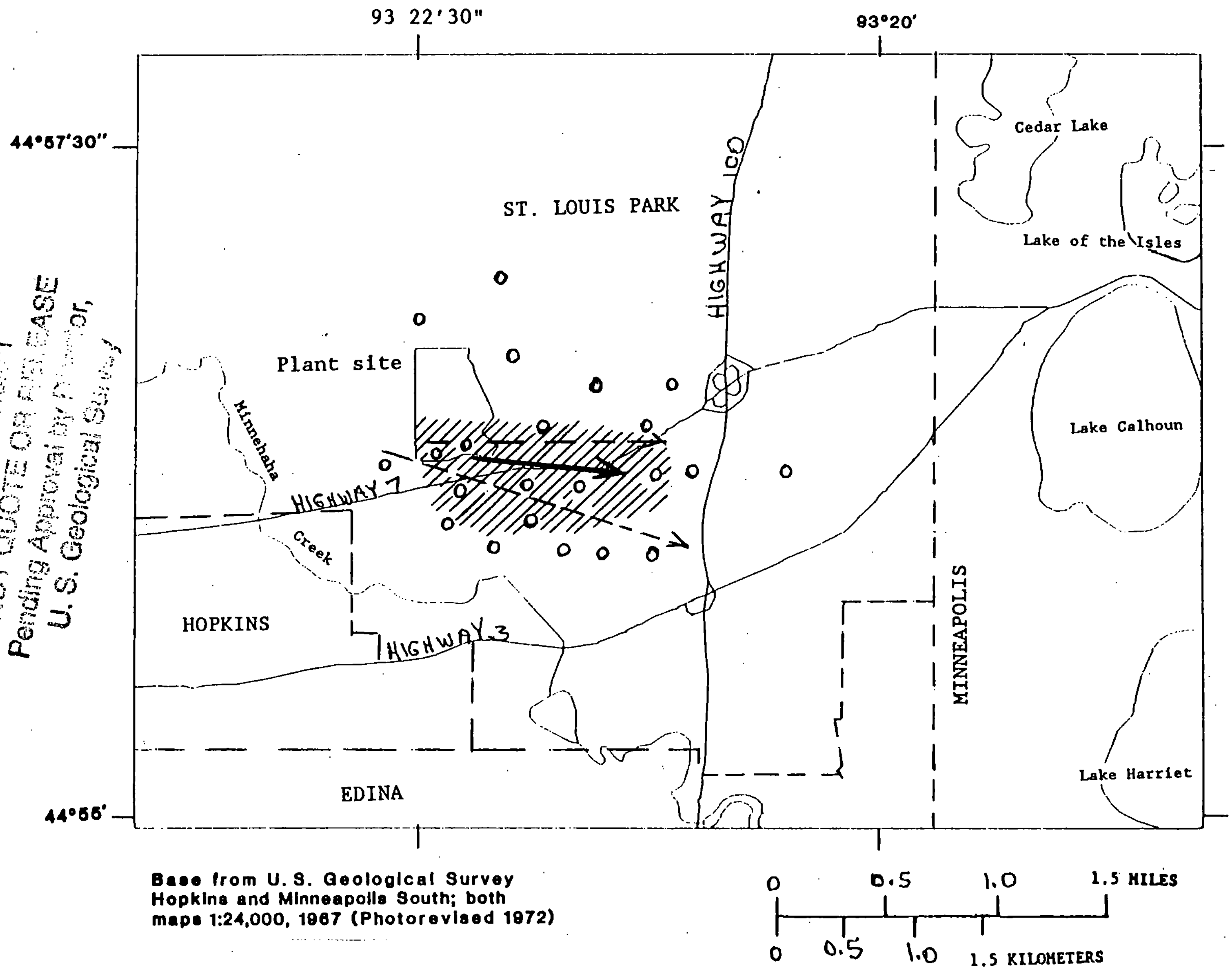


Figure 16.--Path-line plot representing movement through the aquifer system of recharge water derived from the infiltration of precipitation with the vertical hydraulic conductivity of the lower drift confining unit increased by a fact[illegible]f 100 in the western part of the modeled cross-section (trac[illegible] section shown in fig. 2)

EXPLANATION

PARTICLE PATH LINES--Forward-tracking from the recharge (land) surface. Solid areas result from the convergence of path lines



Base from U. S. Geological Survey Hopkins and Minneapolis South; both maps 1:24,000, 1967 (Photorevised 1972)

Figure 17.--Inferred area of contamination in drift and Platteville aquifer system reported by the Minnesota Pollution Control Agency

EXPLANATION

INFERRED AREA OF CONTAMINATION (OF AT LEAST ONE HYDROGEOLOGIC UNIT) IN DRIFT-PLATTEVILLE AQUIFER SYSTEM

o MONITORING WELL

→ AXIS OF CONTAMINATION PLUME

- - → DIRECTIONS OF GROUND-WATER FLOW

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DRAFT

SUPERFUND PRELIMINARY SITE CLOSE OUT REPORT
UNIVERSITY OF MINNESOTA ROSEMOUNT RESEARCH CENTER SUPERFUND SITE
ROSEMOUNT, MINNESOTA

I. INTRODUCTION

This Preliminary Close Out Report documents that the University of Minnesota (University) has completed construction activities for the polychlorinated biphenyl (PCB) soil (and concrete) and ground water cleanup at the University of Minnesota Rosemount Research Center (UMRRC) Site in accordance with the Office of Solid Waste and Emergency Response Directive(OSWER) 9320.2-3C, the Response Action Agreement between the University and the Minnesota Pollution Control Agency (MPCA), dated May 30, 1985, and the June 1990 Record of Decision (ROD) approved by the MPCA and concurred upon by the United States Environmental Protection Agency (EPA). The EPA and MPCA staff conducted the pre-final inspection on September 24, 1993 and determined that the University had constructed the remedy in accordance with Remedial Design (RD) plans and specifications. Activities necessary to achieve site completion are under way.

II. SUMMARY OF SITE CONDITIONS

Background

The UMRRC is located within the city limits of Rosemount in Dakota County, approximately 20 miles southeast of the Minneapolis/St. Paul metropolitan area. The UMRRC covers approximately 5 square miles and is used by some light manufacturing and service companies. Within the confines of the UMRRC, the UMRRC site consists of three industrial disposal sites: the George's Used Equipment (GUE) site, the Porter Electric and Machine Company (PE) site, and the U.S. Transformer (UST) site. The University also burned discarded laboratory chemicals in a burn pit area on the Site.

Soil and concrete on the three disposal sites were contaminated by PCBs and by lead and copper at the GUE site. PCBs in the soil were as high as 63,000 parts per million (ppm) and lead was as high as 40,000 ppm. Also ground water at the site was contaminated by chloroform from the burn pit area. The highest concentration of chloroform found was 72 parts per billion (ppb) in a monitoring well one mile from the burn pit.

The GUE site was used as an electrical equipment storage and salvage facility, as well as a general salvage facility between 1968 and 1985. Activities at this site resulted in soil and concrete contamination by lead and PCBs. The PE site was used for storage and reconditioning of used industrial electrical equipment. Soil at this site is contaminated by PCBs. The UST site was used